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Utilizing Extended Continental Shelf (ECS) and Ocean Exploration Mapping Data for Standardized Marine Ecological Classification of the U.S. Atlantic Margin

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UTILIZING EXTENDED CONTINENTAL SHELF (ECS) AND OCEAN EXPLORATION MAPPING DATA FOR STANDARDIZED MARINE ECOLOGICAL CLASSIFICATION OF THE U.S. ATLANTIC MARGIN

BY

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DISSERTATION

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In preparation for submission to scientific journal.

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Dornback recorded video substrate annotations for several ROV dives used in the study. The manuscript was reviewed and revised by L. Mayer and G. Masetti.

Dedication

This thesis is dedicated to my wife Katia Sowers. The only person with as much time and energy invested in this endeavor as I have – thank you for picking up the slack for me in all other aspects of our life together. I never could have run down the dream of a front row seat exploring the world's oceans and seeking to contribute to this field without your tireless support and love. You remain the best discovery that ever came my way.

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ABSTRACT

UTILIZING EXTENDED CONTINENTAL SHELF (ECS) AND OCEAN EXPLORATION MAPPING DATA FOR STANDARDIZED MARINE ECOLOGICAL CLASSIFICATION OF THE U.S. ATLANTIC MARGIN

by

Derek C. Sowers

University of New Hampshire

Accurate maps of ocean bathymetry and seafloor habitats are needed to support effective marine ecosystem-based management (EBM) approaches. The central premise of this thesis was to synthesize geomorphological elements of large regions of the deep ocean seafloor to establish standards of characterization for ecosystem-based classification. The approach was to apply semi-automated characterization techniques on seafloor bathymetric data that were originally collected for other purposes. The purpose of generating these maps is ultimately to apply to informing ecosystem-based management for large marine regions. While seafloor classification techniques for habitat classification have been applied in shallow water and generally over more local regions, these techniques have never before been applied at continental-margin scales in such deep water.

Over the past decade, the United States has made a substantial investment in seafloor mapping efforts covering over 2.5 million square kilometers of the nation's potential extended continental shelf (ECS) regions, which extend into deep ocean areas beyond 200 nautical miles from the nation's shoreline. The entire potential ECS region off the U.S. Atlantic margin has been mapped by researchers at the University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC). Extensive complimentary mapping datasets collected by the National Oceanic and Atmospheric Administration's Office of Ocean Exploration and Research (NOAA OER) have been acquired in adjacent U.S. waters off the East Coast covering the continental slope submarine canyons region and a majority of the Blake Plateau. The focus of this thesis is on demonstrating that data gathered with the initial purpose of establishing a potential extended continental shelf claim can further be used to support EBM efforts and sound marine spatial planning. The approaches developed here could be effectively applied to ECS and ocean exploration data sets collected world-wide to leverage substantial additional value from broad-scale ocean mapping efforts.

This thesis posited and tested three hypotheses: 1) Broad-scale bathymetric data of the U.S. Atlantic margin collected for ECS and deep sea exploration purposes are useful to consistently classify ecological marine units of the seafloor and generate value-added characterization maps of large regions. 2) Transparent, repeatable, and efficient semi-automated geomorphic analysis methods employing the Coastal and Marine Ecological Classification Standard (CMECS) as an organizational framework produce useful habitat characterization maps of the U.S. Atlantic margin. 3) Vulnerable cold-water coral (CWC) habitats are identifiable and able to be inventoried and characterized using geomorphic analysis and CMECS classification of bathymetric data. These three research hypotheses were tested through classification and characterization studies of three distinct regions of the U.S. Atlantic margin at different scales (an individual seamount feature, the continental slope and abyssal plains, and a continental margin borderland) ranging across a diversity of marine habitats. An automatic segmentation approach to initially identify landform features from the bathymetry of these study areas was completed and then translated into CMECS classification terminology.

Geomorphic terrain classification methods were applied to the continental slope and the abyssal plain of the U.S. Atlantic margin ECS region covering a 959,875 km^2 area. Landform features derived from the bathymetry were then translated into complete coverage geomorphology maps of the region utilizing CMECS to define geoforms. Abyssal flats made up more than half of the area (53%), with the continental slope flat class making up another 30% of the total area. Flats of any geoform class (including continental shelf flats and guyot flats) made up 83.06% of the study area. Slopes of any geoform classes make up a cumulative total of 13.26% of the study region (8.27% abyssal slopes, 3.73% continental slopes, 1.25% seamount slopes), while ridge features comprise only 1.82% of the total study area (1.03% abyssal ridges, 0.63 continental slope ridge, and 0.16% seamount ridges).

Using methods developed to classify the ECS dataset, bathymetric data from twenty multibeam sonar mapping surveys of the Blake Plateau region were used to derive a standardized geomorphic classification capable of quantifying cold-water coral (CWC) mound habitats. Results documented the most extensive CWC mound province thus far discovered and reported in the literature. Nearly continuous CWC mound features span an area up to 472 km long and 88 km wide, with a core area of high density mounds up to 248 km long by 35 km wide. A total of 59,760 individual peak features were delineated, providing the first estimate of the overall number of potential CWC mounds mapped in the Blake Plateau region to date. Five geomorphic landform classes were mapped and quantified: peaks (342 km^2), valleys (2,883 km^2), ridges (2,952 km^2), slopes (15,227 km^2), and flats (49,003 km^2). The complex geomorphology of eight subregions was described qualitatively with geomorphic “fingerprints” and quantitatively by measurements of mound density and vertical relief. Ground-truth from 23 submersible dive videos revealed coral rubble to be the dominant substrate component within the peak, ridge, and slope landforms explored, thereby validating the interpretation of these bathymetric features as CWC mounds. Results indicated that the Blake Plateau supports a globally exceptional CWC mound province of heretofore unprecedented scale (at least for now) and diverse morphological complexity.

This dissertation has successfully characterized the geomorphology of vast regions of the deep ocean floor off the U.S. Atlantic margin for ecosystem-based management purposes. It has applied techniques and established standards of classification that can be applied to other regions throughout the World. This latter point is critical as there are ongoing international efforts today to map the entirety of the World's oceans at meaningful scales and these techniques can synthesize this information in meaningful ways. Furthermore, the need for such syntheses is paramount in order to successful manage (conserve and preserve) the living and non-living resources of the ocean. This thesis shows a way forward for such endeavors, and emphasizes 1) the applicability of data acquired for other purposes to be applied to this purpose, and 2) the need for standards to define and describe marine habitats so that all governments, managers, biologists, geoscientists, and other ocean stakeholders communicate using the same language.

Chapter 1

Introduction

Knowledge about deep sea environments is undergoing a revolution driven by technological advances, increases in financial and political commitments to ocean mapping and ocean observing capabilities, and global efforts by the scientific community to better standardize, manage, and synthesize massive datasets. There has been a veritable explosion in the gathering of deep sea ocean mapping data over the past twenty years driven forward by nations assessing the potential for extending their juridical continental shelves under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) beyond 200 nautical miles – what will be referred to here as the Extended Continental Shelf (ECS). Along with government-sponsored ECS mapping, philanthropic ocean exploration initiatives and marine industries seeking to map areas for potential resource extraction or infrastructure placement continue to collect ocean mapping data. These trends in deep sea exploration are forecasted to continue expanding, and international recognition of the importance of exploring and mapping the deep sea is being formalized and accelerated through many partnerships including the Seabed 2030 initiative (Mayer, et al., 2018).

At the same time that our knowledge of the deep sea is exponentially expanding, so are the stressors exerted on our oceans. The deep ocean is the largest ecosystem on Earth by far, comprising 90% of the livable volume on the planet (Levin and Le Bris, 2015). This ecosystem is challenged with serious threats from pollution (Thevenon et al., 2014), overfishing (Norse et al., 2012), climate change impacts including ocean acidification (FAO, 2019), and the emerging potential impacts of deep sea mining (Miller et al., 2018).

Addressing the conservation challenges facing the deep sea requires an ecosystem-based management (EBM) approach (McLeod et al., 2005), while leveraging the maximum value from newly acquired spatial datasets about these ecosystems. Marine habitat mapping provides the fundamental spatial framework for EBM (Harris and Baker, 2019). The focus of this thesis is therefore on determining pragmatic methods aimed at extracting useful marine habitat characterization information from ECS and exploration mapping bathymetry data – thereby dramatically leveraging the value of the millions of dollars spent on deep sea mapping efforts.

1.1 Extended Continental Shelf (ECS) and Ocean Exploration Mapping Data off the U.S. Atlantic Margin

Vast areas of the seafloor along Earth's continental margins lay within zones beyond the 200 nautical mile (nm) Exclusive Economic Zone (EEZ) within which coastal states may have sovereign rights over the resources of the seafloor and subsurface, if the coastal state can demonstrate that the morphology of the seafloor meets certain criteria outlined in Article 76 of UNCLOS. UNCLOS specifies a complex set of formulae that a coastal state must use to define the limits of the "Extended Continental Shelf (ECS)" area. These formulae are based on the depth and shape of the seafloor as well as the sediment thickness. Two fundamental data requirements needed to delineate potential ECS areas are bathymetric maps and seismic reflection data (U.S. Extended Continental Shelf Project, 2020). As of October 29, 2020 eighty-five submissions have been received by the Commission (U.N. Oceans & Law of the Sea, 2020).

Many of the countries that have provided submissions, or have interest in prospective future submissions, have undertaken broad data gathering efforts within potential ECS areas adjacent to their EEZs, in most all cases involving the acquisition of extensive acoustic seabed mapping data, including bathymetry, bottom backscatter, and seismic reflection.

ECS data are gathered in areas that are typically very poorly explored, and certainly not well characterized from a marine habitat standpoint. While the purpose of collecting ECS data sets are typically focused only on the mapping information needed to address Article 76 requirements, these data sets also offer the opportunity to provide an initial baseline characterization of the seafloor. This baseline can be analyzed in combination with other physical and biological datasets as a first step in understanding the marine ecosystems in these areas thereby offering a tremendous value-added product from the original ECS data.

While the United States Senate has not yet provided advice and consent for the United Nations Convention on the Law of the Sea, the U.S. has undertaken an ambitious campaign to collect and analyze the data required to define its potential ECS area. Over the past decade, the United States has made a substantial investment in seafloor mapping efforts covering over 2.5 million square kilometers of the country's potential ECS regions – an area the size of Alaska and Texas combined (U.S. Extended Continental Shelf Project, 2020). Data gathering with high resolution multibeam sonar data to define the foot of the continental slope and the 2500 m isobaths has been a major focus of effort (Center for Coastal and Ocean Mapping Joint Hydrographic Center, 2020). In the Atlantic, multibeam sonar data have been collected in ECS areas by the University of New Hampshire's Center for Coastal and Ocean Mapping / Joint Hydrographic Center (CCOM/JHC) on eight cruises between 2004 and 2015, using 12-kHz

Kongsberg EM120 or EM122 multibeam sonars (bathymetry resolution of 100 m). Data were acquired with the initial purpose of supporting the determination of the outer limits of the U.S. juridical continental shelf consistent with international law.

In addition to the ocean mapping datasets collected for ECS purposes, extensive complimentary mapping datasets have been acquired in deep sea regions off the U.S. Atlantic coast by the National Oceanic and Atmospheric Administration's Office of Ocean Exploration and Research (NOAA OER) using NOAA Ship *Okeanos Explorer*. Data were collected during 31 cruises using a 30-kHz Kongsberg EM302 multibeam sonar (with a bathymetric grid resolution of 20-50 m) between 2011 and 2019. The combined spatial coverage of Atlantic margin ECS and OER multibeam sonar bathymetry data collected through 2019 and used in this thesis is shown in **Figure 1.1** (Johnson, 2020).

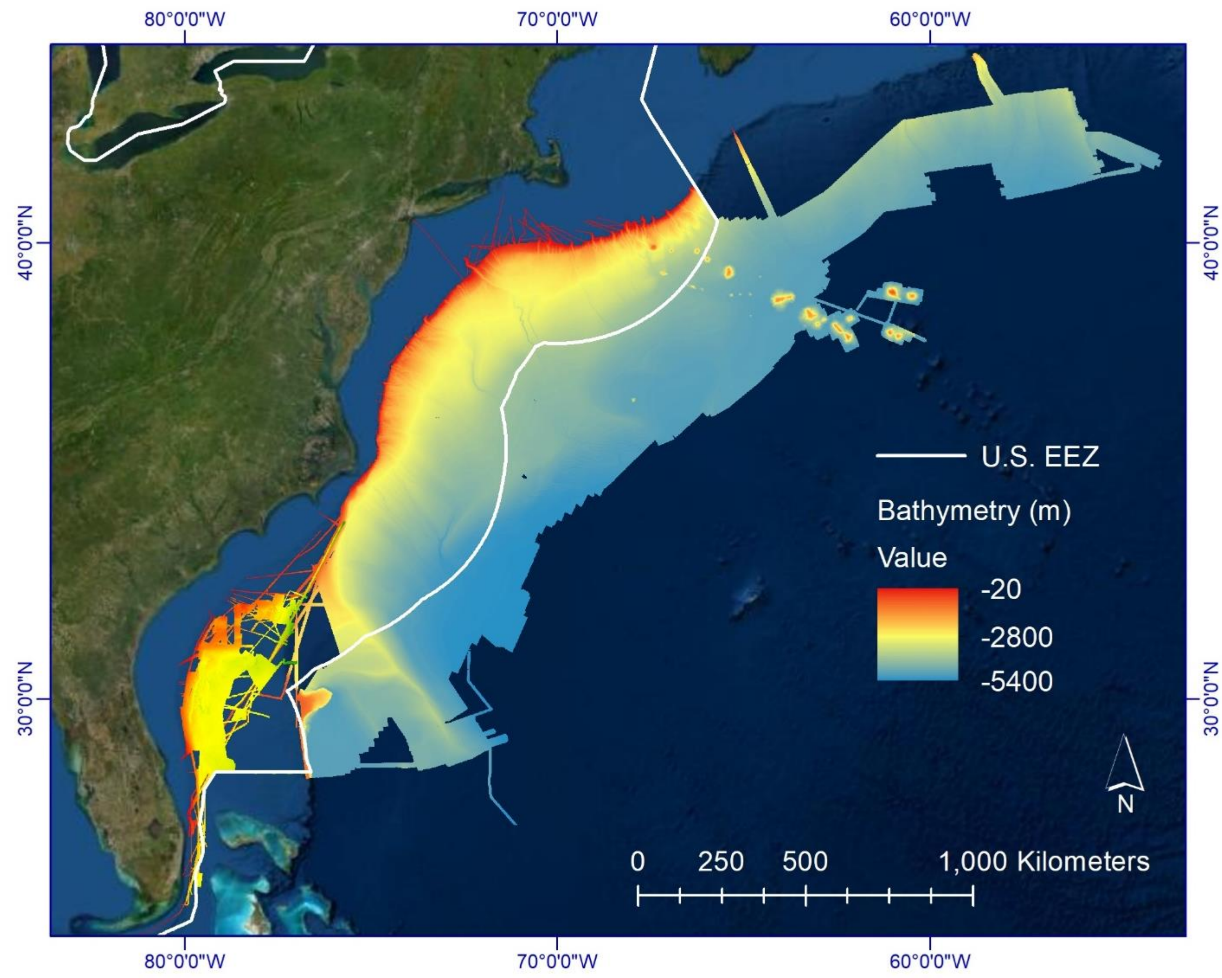

Figure 1.1 Coverage of combined color-coded bathymetry dataset of ECS and NOAA OER mapping efforts completed off the Atlantic Continental margin as of 2019 and used in this thesis. The data extends from the shelf break to the abyssal ocean, and from Florida to beyond the U.S./Canada border. Bathymetric synthesis credit: Paul Johnson, UNH CCOM/JHC.

The completion of these high cost and high quality datasets presents a rich opportunity to utilize these data for supporting numerous other ocean research and management priorities facing the United States. The thesis presented here establishes a data synthesis and marine habitat classification approach that leverages and increases the value of existing ECS and ocean exploration data. This effort is focused on the Atlantic margin of the U.S., but can be applied to other ECS and deep ocean regions in the U.S. and abroad.

1.2 Ecosystem-Based Management and Approaches to Marine Habitat Mapping

The 2003 Pew Ocean Commission report, *America's Living Oceans: Charting a Course for Sea Change*, and the 2004 U.S. Commission on Ocean Policy report, *An Ocean Blueprint for the 21st Century*, provided a detailed roadmap of recommendations for improvements in many aspects of ocean and coastal policy. Both commissions articulated failures in current marine ocean management approaches and called for an integrated ecosystem-based approach referred to as “ecosystem-based management” (EBM). The Scientific Consensus Statement on Marine Ecosystem-Based Management (McLeod et al., 2005) defines EBM for the oceans as:

> an integrated approach to management that considers the entire ecosystem, including humans. The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive and resilient condition so that it can provide the services humans want and need. Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern; it considers the cumulative impacts of different sectors.

Actions consistent with EBM include: ecosystem-level planning, establishing cross-jurisdictional management goals, regional area-based management and establishment of marine reserves, and support of long-term ocean research and monitoring programs (McLeod et al., 2005). These policy changes are significantly altering how ocean management is conducted and dramatically increasing the need for accurate maps of ocean bathymetry and marine habitat that serve as the fundamental basis for understanding marine ecosystems and guiding marine spatial planning efforts.

“Habitat” is a general term and is defined differently depending on whether one is seeking to map suitable areas for single species, distinct communities of species, or areas that represent a gradient of abiotic properties as a proxy for the actual distribution of organisms (Brown et al., 2011). Seafloor habitats can be defined as "physically distinct areas of seabed that are associated with particular species, communities, or assemblages that consistently occur together" (Harris and Baker, 2011a).

The primary motivations for characterizing and classifying marine habitats are to:

1) Synthesize diverse biological, physical, and chemical datasets into interpreted products that help to better understand and model marine ecosystems (often desirable for marine scientists); and
2) Support marine management decisions that require spatially-relevant data (often desirable for management agencies, political entities, industries, and conservationists).

Demand for marine habitat classification is being driven by increasing pressures on marine environments, the establishment of increasingly regional-scale management approaches to the oceans, and efforts to implement EBM practices.

To produce benthic habitat maps continuous coverage environmental data is needed in combination with representative *in situ* "ground-truth" samples. Continuous coverage datasets can include directly measured data such as bathymetry and backscatter, as well as outputs from oceanographic models that are based on measured data (e.g. currents, temperature, salinity, productivity models). *In situ* samples routinely used to inform benthic habitat characterization include sediment grabs and cores, videos, photographs, and biological samples. As informed by the *in-situ* samples, the complete coverage data are then typically used as a proxy for the distribution of potential habitats (MESH, 2008a).

In a useful overview of the use of acoustic methods in support of benthic habitat mapping, Brown et al. (2011) summarized three basic strategies to producing benthic habitat maps:

1) Utilize abiotic surrogates (unsupervised classification - limited or no ground validation)

The abiotic surrogacy approach generates marine landscape (seascape) maps at broad spatial scales based on delineating physiographic features from continuous datasets. In the absence of perfect knowledge of marine biodiversity and species-habitat relationships (which is unachievable), in many settings coarser level classification of marine habits that support precautionary management of a diversity of habitat types can serve as a surrogate for protections and management schemes for individual species. The abiotic features are thereby used as proxies to infer potential habitat suitability. This approach can be effective for species or communities with distributions closely tied to remotely measured seafloor characteristics (e.g. coral reefs), but often poorly predicts species distribution at fine spatial scales.

2) Assemble first, predict later (unsupervised classification)

The “assemble first, predict later” approach is referred to as a “top-down” strategy where the environmental data is segmented into spatial units and then correlated with ground-truth data to examine statistical relationships between abiotic and biotic variables. Correlations can then be extrapolated to predict potential habitat over larger areas.

3) Predict first, assemble later (supervised classification)

The “predict first, assemble later” category is a bottom up strategy that uses the ground-truthing data as a means to segment the abiotic environmental data. By examining the environmental conditions within which the habitat occurs, a species or habitat distribution model is developed and then used to classify the broader environmental data sets into areas that are most suitable to support that habitat type.

Use of geological surrogates as coarse predictors of seafloor habitat (strategy 1) has shown promising results in several studies (e.g. Althaus et al., 2012; Kloser et al., 2007), and this approach is a highly active subject of research (Brown et al., 2011). Practically speaking, this approach is currently one of the only options when seeking to classify habitats at a regional scale with little available ground-truth data (i.e. much of the deep sea beyond the edge of the continental shelf).

The thesis work presented here adopted strategy 1 given the vast spatial scale covered and the lack of accurate ground-truth information available for most of the area covered. In some areas where ground-truth data were collected by recent submersible dives with good georeferencing these data were used as part of the classification process.

1.3 Standardized Classification of Marine Habitats

Standardized classification methodologies for terrestrial and freshwater habitats have been robustly developed and are broadly used (FGDC, 1996, 2008). By providing a standardized "common language" to describe habitats, these classification approaches have demonstrated their utility for informing landscape-scale management and conservation decisions. Generating full coverage remote sensing datasets and statistically-representative samples of marine habitats is more difficult than on land, and thus the field of marine habitat classification is comparatively nascent.

The development of interpreted ecological classification maps via the synthesis of diverse marine datasets is being undertaken in numerous countries around the world. In many cases this work is done on continental shelf habitats for relatively small areas of high management interest (Harris and Baker, 2011b). Notable examples of classification work covering larger and/or deeper areas of the ocean include Canada's National Marine Mapping Strategy (Pickrill, 2007; Pickrill and Kostylev, 2007), Ireland and the United Kingdom (Conner et al., 2004), Norway (Kartverket, 2015), Europe (MESH, 2008), and Australia (Geoscience Australia, 2015).

While there is much work going on in this field, there has been little agreement on standardized classification methodology among different studies (Harris and Baker, 2011b), which leads to difficulties in directly comparing the outcome of these efforts. Standardized ecological classification schemes offer a coherent way to structure knowledge gained about these areas. The benefits of standardized classification schemes become particularly important when synthesizing marine habitat information at the regional level covering many marine datasets and management jurisdictions. In Europe, efforts to promote standardization have resulted in the European Nature Information System (EUNIS) (EEA, 2004).

In the United States, the Coastal and Marine Ecological Classification Standard (CMECS) has been adopted as the federal standard for classifying marine habitats (FGDC, 2012). CMECS provides a framework for organizing data about the marine environment so that ecosystems can be identified, characterized, and mapped in a standard way across regional and national boundaries (NOAA, 2015). The purpose of CMECS is to provide a common language to describe coastal and marine ecological features in order to:

- classify the geological, physical, biological, and chemical components of the ocean

- integrate data from different sources and study areas
- facilitate regional assessment

As shown in **Figure 1.2**, CMECS is organized by six main components that characterize various aspects of the seascape: aquatic setting, biogeographic setting, water column, geoform, substrate, and biotic communities. Each component is a stand-alone construct that can be used on its own or in combination with other elements of the classification standard (FGDC, 2012). The geoform component describes the major geomorphic characteristics of the seafloor. Important pilot and case studies utilizing CMECS have been completed, but the standard is yet to be fully adopted in practice and fully utilized by researchers and managers throughout U.S. marine waters (personal communication, Mark Finkbeiner, May 28, 2015).

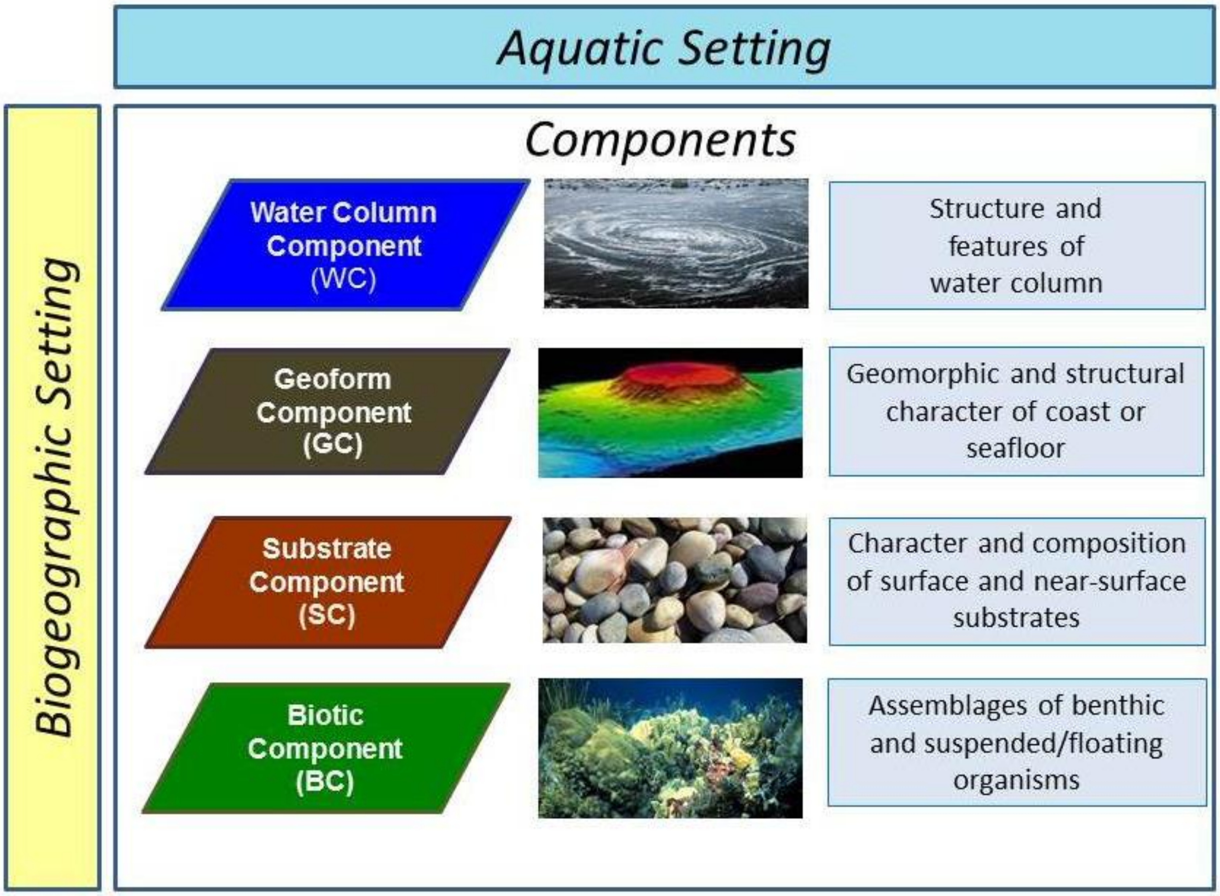

Figure 1.2 CMECS Settings and Components (Figure from FGDC, 2012)

Given that the focus of this thesis is on seafloor classification, the geoform, substrate, and biotic (where ground-truth data of sufficient quality existed) components of CMECS were utilized. The water column component of CMECS was beyond the scope of this thesis.

This thesis utilizes CMECS as an organizational framework to integrate and interpret diverse available marine datasets within a large region covering deep water habitats of the continental slope and abyssal areas both within the U.S. EEZ and in the potential ECS area of the Atlantic margin. This work fills a gap in the field of marine habitat mapping since few habitat mapping studies have been done in slope or abyssal habitats (Harris and Baker, 2011b).

Inasmuch as many nations are collecting acoustic mapping data for ECS purposes, the research presented here provides insights into the benefits and limitations of also using these data to inform deep sea habitat characterization and EBM.

1.4 Challenges in Characterizing Marine Habitats

While the demand for improved marine habitat maps is clear, determining effective approaches for generating these maps is still an area of active research that faces many challenges. Several of the key challenges in this field include:

1. Technical challenges in fully utilizing acoustic backscatter intensity data to assess properties of the seafloor (Fonseca et al., 2009; Fonseca and Mayer, 2007; Hughes Clarke, 1994; Rzhanov et al., 2012).
2. Assessing how well geologic properties of the seafloor serve as proxies for certain types of marine habitat (Beaman and Harris, 2007; Brown et al., 2001; McArthur et al., 2010).
3. Recognition that the spatial and temporal scales of importance in structuring marine community assemblages are often poorly understood or unknown. (Census of Marine Life, 2010; FGDC, 2012).
4. Difficulties in synthesizing data collected by various researchers, for different purposes, lacking a standardized classification scheme (Harris and Baker, 2011b).
5. Determining appropriate methods to synthesize datasets of highly variable scale and resolution in order to generate maps (Dolan and Lucier, 2014).
6. The limited availability of samples of seafloor habitats (particularly in the deep sea), and the cost of obtaining these samples (OBIS, 2013).

7. The lack of transparency of marine ecological classification efforts that employ "black-box" geospatial analyses (Lecours, 2017), and the lack of repeatability for one-time classification methods that rely primarily on expert judgement.

1.5 Purpose of the Study

This dissertation was targeted to make contributions towards addressing aspects of challenges 4 to 7 described above in section 1.5 with respect to the field of marine habitat mapping.

The primary research question of this thesis is: Can multibeam data from the deep water Atlantic margin, along with other existing ancillary datasets, be utilized to generate standardized marine ecological classification maps of the seafloor useful for supporting ecosystem-based management (EBM)?

Specifically, this thesis posits the following hypotheses:

1. Broad-scale bathymetric data of the U.S. Atlantic margin collected for ECS and deep sea exploration purposes are useful to consistently classify ecological marine units of the seafloor and generate value-added characterization maps of large regions.
2. Transparent, repeatable, and efficient semi-automated geomorphic analysis methods employing the Coastal and Marine Ecological Classification Standard (CMECS) as an organizational framework produce useful habitat characterization maps of the U.S. Atlantic margin.

3. Vulnerable cold-water coral (CWC) habitats are identifiable and able to be inventoried and characterized using geomorphic analysis and CMECS classification of bathymetric data.

These three research hypotheses were tested through classification and characterization studies of three distinct regions of the U.S. Atlantic margin at different scales ranging across a diversity of marine habitats. Results of each of these applications are structured into three separate but tightly related research journal articles. Each of these journal articles represents a chapter in this dissertation (Chapters 2-4). Each article contains its own abstract, background context, study area description, detailed methods explanation, results, discussion, and conclusion. A brief synopsis of each paper, and how it relates to the central hypotheses of this dissertation, is described below. Chapter 2 and Chapter 3 have been published as a peer-reviewed book chapter and a scientific journal article, respectively. Chapter 4 is in preparation for submission to a peer-reviewed journal. Chapter 5 provides a synthesis of the overall conclusions of the thesis based on insights from the articles in Chapters 2-4.

<u>Chapter 2 Title:</u>

Application of the Coastal and Marine Ecological Classification Standard to Gosnold Seamount, North Atlantic Ocean

<u>Synopsis:</u> This paper is a case study completed on Gosnold Seamount in the New England Seamount Chain as a proof-of-concept over a relatively small area in order to develop and refine methods aimed at addressing the dissertation hypotheses. The paper developed analytical workflows that were refined in subsequent chapters and applied to larger study regions. A key advancement from this work was recognizing the utility of a new bathymetry and backscatter

spatial analysis tool called BRESS, the Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation (Masetti et al., 2018), for systematic delineation of terrain landforms suitable for translation to CMECS geoforms. The study also generated CMECS biotic and substrate component classifications based on fine-scale observations of biota and substrate from a remotely operated vehicle (ROV) dive on the seamount. The study largely validated the utility of using CMECS as a systematic classification framework for a deep sea seamount, but also proposed some new provisional CMECS units tailored for this setting. This paper was published as a chapter in the book Seafloor Geomorphology as Benthic Habitat, Second Edition (Harris and Baker, 2020).

<u>Chapter 3 Title:</u>

Standardized Geomorphic Classification of Seafloor Within the United States Atlantic Canyons and Continental Margin

<u>Synopsis:</u> This study took insights learned from Chapter 2 and scaled the methods for systematic geomorphic classification to a dramatically larger region spanning the continental shelf break to the abyssal plains, from Canada to Florida. The study utilized input bathymetric data from eight ECS cruises and nine OER cruises to derive complete coverage standardized geomorphology maps of the region using CMECS to define geoforms. The study demonstrated the utility of this approach for inventorying and quantifying areas of each geoform class. The clear advantages of an automatic terrain segmentation approach (versus manual delineations) for classifying vast ocean areas was a fundamental highlight of this paper. The highly diverse terrain covered by this study led to new challenges in parameterizing the terrain analysis tool, and lessons learned from that experience can be used to guide future applications of the method to other ECS regions

spanning large depth and slope gradients. The study also demonstrated the time-and-effort efficiency of classifying such a large geography using a transparent and repeatable strategy. The paper was peer-reviewed by a United States Geological Survey geologist with specialized knowledge of the U.S. Atlantic Margin (Dr. Jason Chaytor), as well as by a well-recognized expert on large-scale geomorphic characterization of marine habitat (Dr. Peter Harris). This paper was published in the journal Frontiers in Marine Science (Sowers et al., 2020).

<u>Chapter 4 Title:</u>

Standardized Geomorphic Characterization of the Extensive Cold-Water Coral Mound Province of the Blake Plateau, USA

<u>Synopsis:</u> Given that work completed for Chapters 2 and 3 established a working methodology for systematic classification of ecological marine units using CMECS terminology, Chapter 4 focuses on the third hypothesis of the dissertation: testing the utility of these methods for identifying, inventorying, and characterizing vulnerable cold-water coral (CWC) habitats. The approach was proven to be highly effective at characterizing individual mound-forming scleractinian coral features exemplified by the morphologies encountered on the Blake Plateau. The approach was also effective at delineating high probability CWC features associated with scarp/ridge complexes in the region that have a mound morphology component to them, as validated by several submersible dives in the region.

While this region has been well documented by other researchers as a globally important CWC mound hotspot, the nearly full extent and sheer number of features has only been revealed with the recent mapping expedition data synthesized and presented in this paper. The research completed in Chapter 4 revealed a total of 59,760 individual peak features, providing the first estimate of the overall number of potential CWC mounds mapped in the region to date. The areal extent of densely aggregated CWC mounds was delineated and used to document the most expansive continuous CWC mound province thus far discovered worldwide. Cumulative areal coverages of geomorphic classes were quantified, and detailed morphological statistics were generated for eight subregions exhibiting highly diverse patterns of mound distribution and vertical relief. Two newly discovered large CWC mound subregions located outside existing coral protection zones were characterized by the study, and this information has been presented directly by the author to the South Atlantic Fishery Management Council. The study methods used were able to quantify characteristics of the CWC mound resources in ways that would have been difficult or impossible to do otherwise. This study therefore effectively demonstrated the usefulness of the standardized geomorphic maps and associated descriptive statistics for supporting ecosystem-based management (EBM) decisions pertaining to a large globally important deep-sea ecosystem.

Chapter 2

Application of the Coastal and Marine Ecological Classification Standard to Gosnold Seamount, North Atlantic Ocean

This article was published in Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats, 2nd Edition, **Sowers, D.**, Dijkstra, J.A., G. Masetti, G., Mayer, L.A., Mello, K., Malik, M., pages 903-916, Copyright Elsevier (2020)

2.1 Summary

This case study applied the Coastal and Marine Ecological Classification Standard (CMECS) to initial characterization of a deep sea seamount by combining observations from a remotely-operated vehicle (ROV) and information derived from multibeam sonar bathymetry and backscatter. Spatial segmentation of the multibeam bathymetry was done using algorithms based on definition of bathymorphons (Masetti et al., 2018) resulting in six classes: flats, slopes, ridges, valleys, shoulders, and footslopes. These classes were modified to delineate CMECS “Level 1” geoform units for Gosnold Seamount. Further segmentation of landforms was completed using textural analysis of the sonar backscatter mosaic of the seamount to identify segments of the same landform type with similar reflectivity texture. ROV dive video of the seafloor was analyzed manually to create a spreadsheet of 933 georeferenced annotations of organisms and associated substrate types. The dominant sediment type over each 50m segment of the ROV track was also classified using substrate unit terminology from CMECS into four

classes: bedrock (10% of ROV track), fine unconsolidated sediments on bedrock (84%), coral rubble (1%), and sand (5%). Eleven genera of corals, 2 classes of sponges and 4 classes of echinoderms were observed along the track, with glass sponges dominating the annotation and abundance counts. Nominal regression revealed that depth, temperature and sediment type were significant predictors of individual coral along the ROV track ($p < 0.001$, $p < 0.001$, $p < 0.001$, respectively at the 0.01 significance level). In contrast, slope, sediment type and dissolved oxygen were significant predictors of sponge distribution along the track ($p < 0.0001$ for all at the 0.01 significance level). In summary, the application of CMECs to Gosnold Seamount provided a useful systematic framework for structuring geoform, substrate, and biotic classification of benthic habitat. This standard, in combination with the semi-automated seafloor segmentation approach utilized, provides a consistent and reproducible habitat classification approach for large regions and facilitate comparison of habitats among features.

2.2 Introduction

Gosnold Seamount (62.51072°N, 38.30238°W) is a prominent dual-peaked guyot rising over 3,350 meters from the abyssal plain as part of the New England Seamount Chain. The New England Seamount Chain consists of over 35 seamounts, and is the longest in the North Atlantic Ocean, extending southeast from Georges Bank about 1,300 km to the outer Bermuda Rise (Taras and Hart, 1987). Duncan (1984) used ^{40}Ar-^{39}Ar dating techniques on rock dredged from Gosnold Seamount and estimated its age at 90 Ma, which corresponds to the Late Cretaceous period. Gosnold Seamount is located 730 kilometers offshore from the New England coast of the United States and covers an area of about 3,780 km^2, with the majority of the flat top of the feature located approximately 1,640 meters below sea level. The guyot is linear in overall form, with a length of 85 km and width of 38 km trending in a northwest to southeast orientation (**Figure 2.1**). Water depths of the benthic habitats on Gosnold Seamount vary from 1,418 m to 5,082 m.

To our knowledge, a rigorous analysis of the naturalness, condition, and trends at Gosnold Seamount has not been completed and the data needed to support a thorough assessment is largely lacking. However, it is reasonable to assume (with medium confidence) that the condition is very good and likely steady. This is based on the geographic isolation of the seamount from land and the fact that the Northwest Atlantic Fisheries Organization (NAFO) has a Vulnerable Marine Ecosystems (VME) closure restricting bottom contact gear throughout the region of the New England Seamount Chain within their jurisdiction until at least 2020 (NAFO, 2018). Fourteen nations are NAFO contracting parties. Potential impacts from illegal bottom-contact fishing and climate change related impacts are unknown.

The first detailed multibeam mapping surveys and remotely operated vehicle (ROV) dive on Gosnold Seamount were completed in 2014 by NOAA's Office of Ocean Exploration & Research (OER) with the NOAA vessel *Okeanos Explorer* as part of the EX-14-04L1 (Sowers et al., 2014) and EX-14-04L3 expeditions (McKenna and Kennedy, 2014). Analysis of the *Okeanos Explorer* multibeam sonar data and the high definition video obtained by the ROV *Deep Discoverer* are the subject of this case study. Bathymetry and backscatter data were collected using the 30 kHz Kongsberg EM 302 multibeam sonar. The 75m resolution multibeam sonar grid resulting from this survey is shown in **Figure 2.1** as an inset to the location map of the study area.

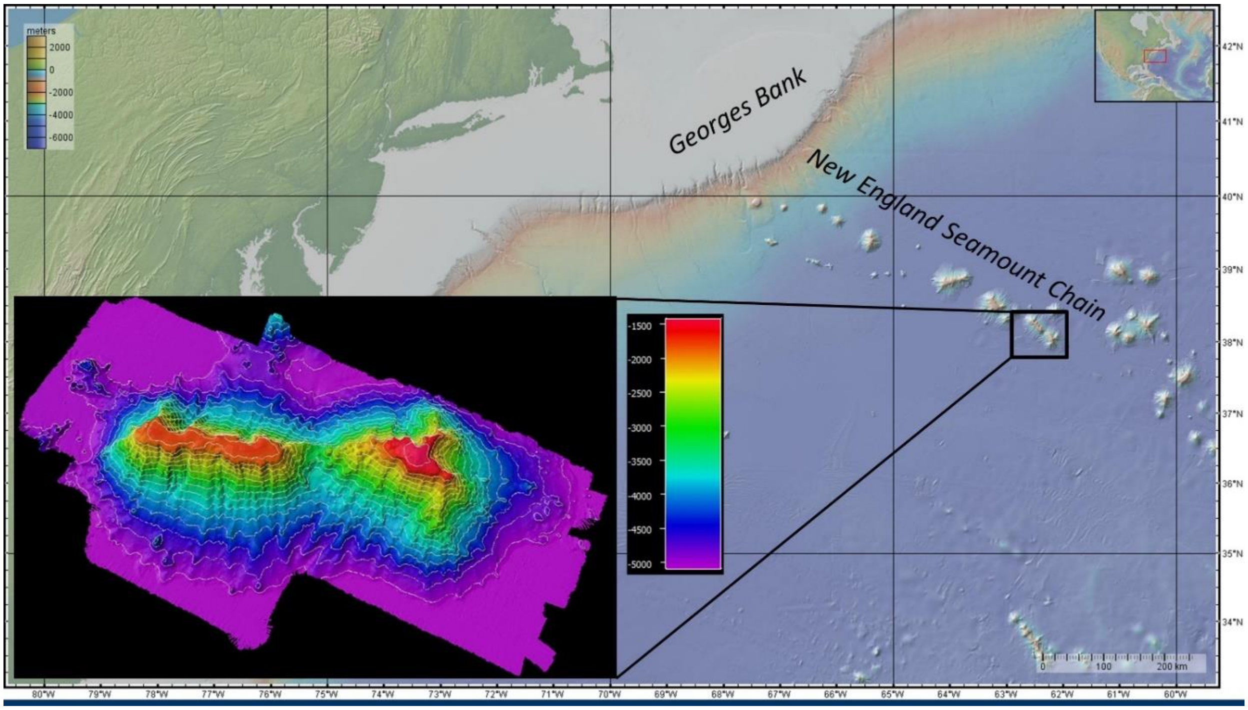

Figure 2.1. Location map for Gosnold Seamount within the New England Seamount Chain in the North Atlantic Ocean. Call out box shows 3D 75m resolution gridded bathymetric terrain of the seamount at 3x vertical exaggeration and depth in meters. Background map generated in GeoMapApp: http://www.geomapapp.org.

High resolution video for this study was obtained for Gosnold Seamount using NOAA OER’s 6,000 meter rated dual-body ROV system, the *Deep Discoverer* (*D2*) and *Seirios* during the EX1404L3 expedition on September 28, 2014. These ROVs are maintained and operated by the Global Foundation for Ocean Exploration. *D2*’s primary data set is high-definition video collected by six HD cameras. In addition, *D2* carries a Sea Bird 9/11+ CTD with Light Scattering (LSS), Dissolved Oxygen (DO), Oxygen Reduction Potential (ORP), temperature, salinity and depth sensors. The second body of the system is the camera platform *Seirios*, which provides additional lighting and an “aerial” view while *D2* investigates the seafloor. The dive track of ROV *D2* on Gosnold Seamount is shown in **Figure 2.2**.

An ultra-short baseline (USBL) system was used to obtain vehicle position relative to the ship during deployment. The ROV was also equipped with lights aimed at the seafloor for illumination. Two laser beams pointing 10 cm apart are projected onto the video image providing a scale to enable calculation of total area analyzed along each segment of the ROV track. The ROV track traversed approximately 800 meters (linear distance) up a distinct ridge feature on the northeast side of the seamount, until reaching the edge of the relatively flat top of the summit. Depths explored ranged from 2126 m to 1851 m (**Figure 2.2**). No physical biological or substrate samples were taken during the ROV dive.

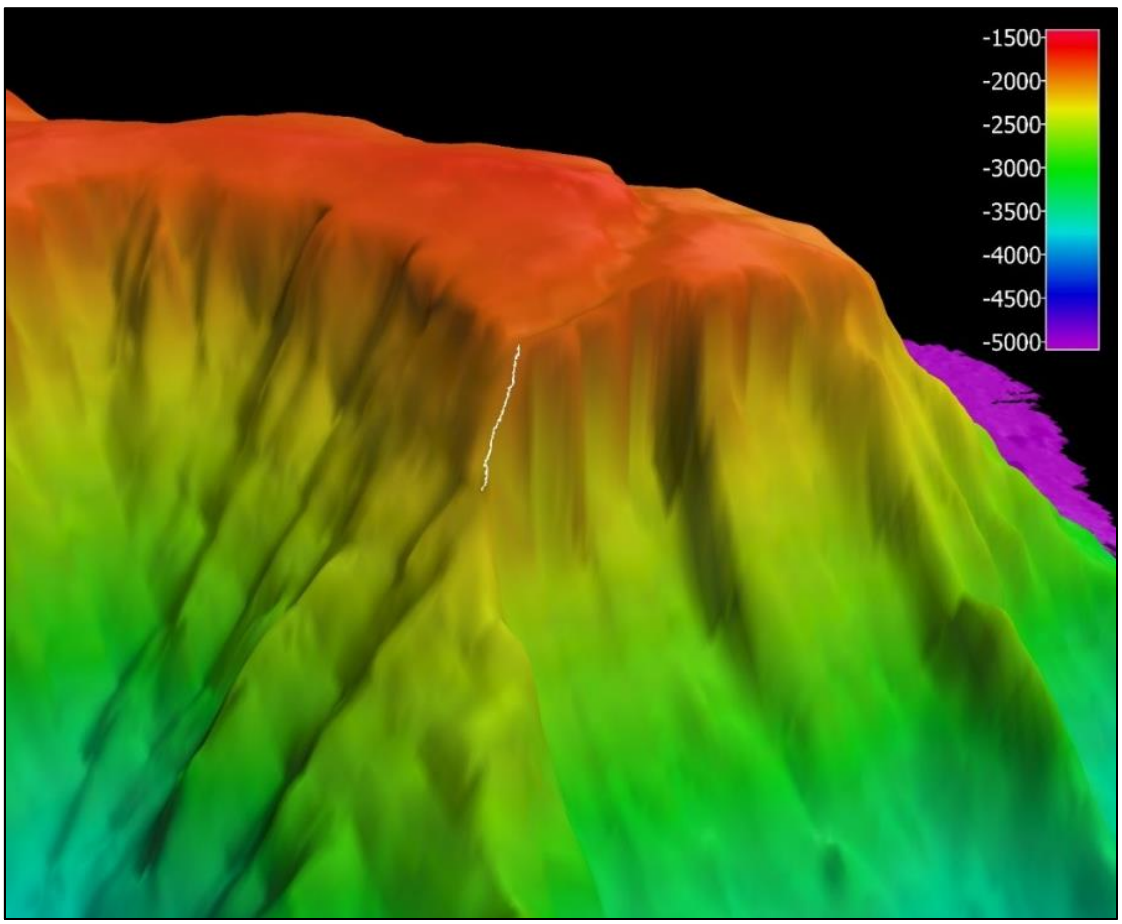

Figure 2.2 Location of the ROV dive track (white line) shown on the bathymetry grid for Gosnold Seamount at 3x vertical exaggeration. Depths shown are in meters.

An overall guiding objective of this study was to systematically apply the Coastal and Marine Ecological Classification Standard (CMECS) to a major deep-sea feature as part of an ongoing effort to refine methods for applying this standard to deep-sea habitats. The benefits of standardized classification schemes become particularly important when synthesizing marine habitat information at the regional level covering many marine datasets and management jurisdictions. CMECS was formally endorsed by the U.S. Federal Geographic Data Committee in 2012 and provides a comprehensive framework of common terminology for classifying biological species, water column properties, and seafloor morphology and composition. For details on the hierarchical structure and units available in CMECS the reader is referred to the official adopted standard document (FGDC, 2012).

Application of CMECS to deep sea habitats is still in the early phases with some important notable efforts completed by NOAA's Deep Sea Coral Research and Technology Program utilizing data from three separate expeditions in the Pacific Ocean (Bassett et al., 2017), and by Ruby (2017) within the Gulf of Mexico. As a dynamic standard, CMECS incorporates the use of provisional units, which allow researchers to add proposed new units to the standard as they are discovered. This flexibility is especially valuable in the deep sea, where knowledge is increasing rapidly and new discoveries are commonplace. This case study shares results of a collaborative effort between NOAA OER and UNH/CCOM to advance pragmatic efforts to apply the standard to deep sea habitats in order to facilitate more meaningful characterization of the geomorphology, biology, substrate, and water column of these poorly-studied habitats.

2.3 Geomorphic Features and Habitats

Utilizing CMECS as an organization framework, Gosnold Seamount was classified using the upper levels of the hierarchy as shown in **Table 2.1.**

Table 2.1. CMECS units for Gosnold Seamount for biogeographic setting, aquatic setting, water column component, and geoform component. For definitions and details see FGDC, 2012.

<u>Biogeographic Setting:</u> • Realm: Temperate Northern Atlantic • Province: Cold Temperate Northwest Atlantic • Ecoregion: n/a (not defined outside national maritime boundaries)
<u>Aquatic Setting:</u> • System: Marine • Subsystem: Marine Oceanic • Tidal Zone: Subtidal
<u>Water Column Component:</u> • Water Column Layer: Marine Oceanic • Salinity Regime: Euhaline Water (30 to <40 PSU) • Temperature Regime: Very Cold (0 to <5 degrees C)
<u>Geoform Component:</u> • Tectonic Setting: Abyssal Plain • Physiographic Setting: Marine Basin Floor • Geoform Origin: Geologic • Level 1 Geoform: Seamount Geoform Type: Guyot

The key inputs to the geomorphic analysis of Gosnold Seamount were a cleaned and quality controlled 75-meter resolution bathymetric grid and a co-located 17 meter resolution multibeam backscatter mosaic of the seamount. The bathymetric grid was produced using Caris HIPS and SIPS software (version 9.0), and the backscatter mosaic was produced using QPS Fledermaus Geocoder Toolbox (version 7.8.1) and corrected for geometric and radiometric effects, with incident angles to the seafloor calculated from a background bathymetric reference grid.

Terrain and acoustic reflectivity analysis in this study utilized the Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation (BRESS) approach developed by Masetti et al. (2018). The BRESS analytical approach implements principles of topographic openness, pattern recognition, and texture classification to identify a collection of homogeneous, non-overlapping seafloor segments of consistent morphology and acoustic backscatter texture. The algorithm first establishes geomorphic elements of the seafloor or “area kernels” based on “bathymorphons”, these latter derived from the “geomorphon” concept developed by Jasiewicz and Stepinski (2013). As a preliminary step, the BRESS algorithm classifies the terrain by landform type, using the calculated bathymorphons and a look-up table. The original geomorphon work proposes a ten-type landform classification: flat, peak, ridge, shoulder, spur, slope, pit, valley, footslope, and hollow. In addition, BRESS offers a simplified six-type landform classification which merges peaks, pits, spurs, and hollows with adjacent morphologies. The simplified option was used in this study, with the output of the bathymetric Digital Elevation Model (DEM) analysis resulting in a continuous landform map of Gosnold Seamount composed of six classes: flat, slope, ridge, valley, shoulder, and footslope (**Figure 2.3**).

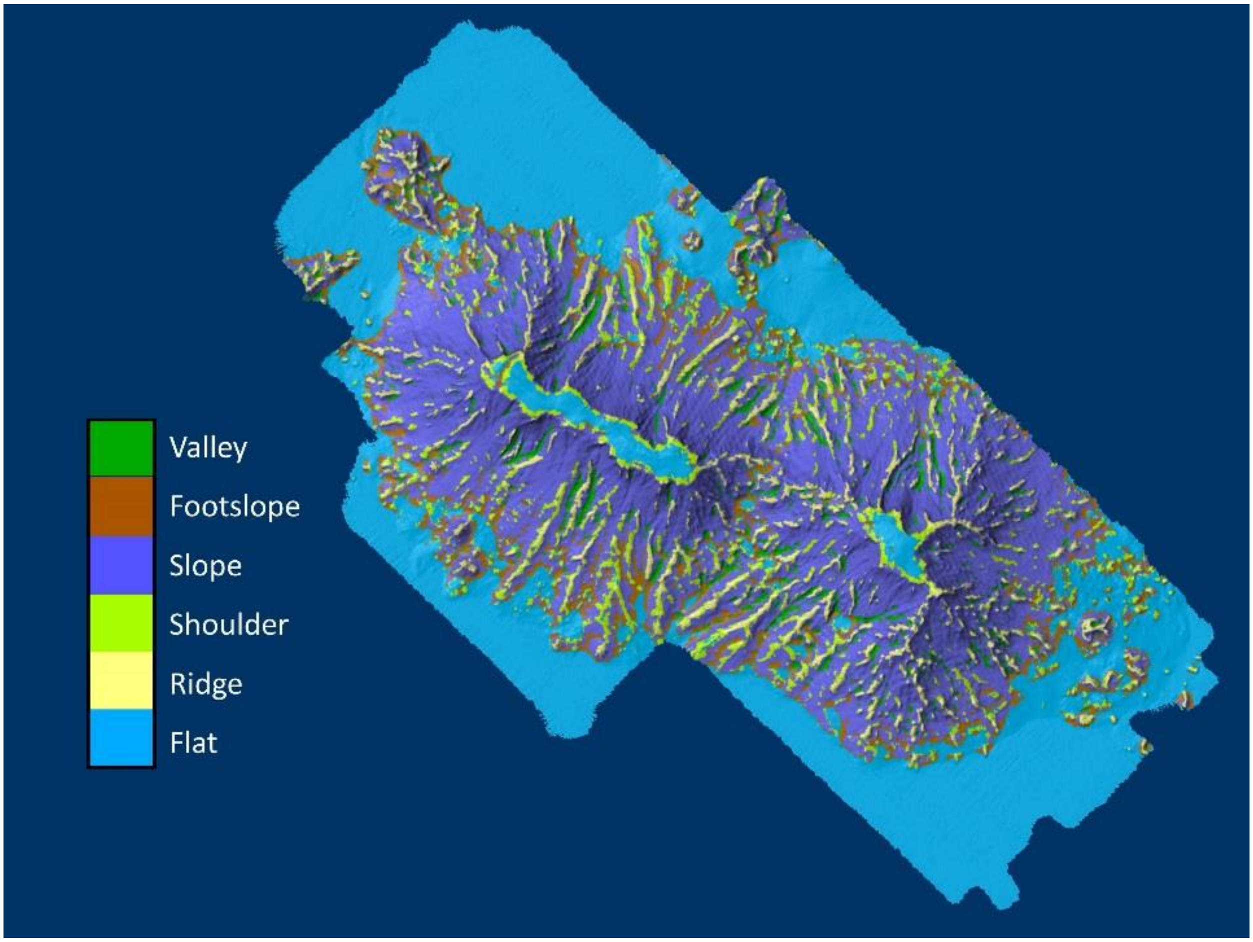

Figure 2.3. Map of landforms ("bathymorphons") delineated for Gosnold Seamount. Note the accentuation of the distinct ridge features (yellow), the flat areas on the top of the guyot and abyssal plain (blue), and the shoulder features (light green) at the transition from the steep slopes to the guyot top.

The landform classes shown in **Figure 2.3** effectively delineated the major features of geomorphic interest on the seamount and can be considered comparable in many ways to the likely output of manual delineations performed by a skilled analyst. Key benefits of the automated classification completed with the BRESS approach are speed, computational efficiency, reproducibility of results (given the same input datasets and analysis parameters), and the ability to apply the same methods to similar features at the regional scale for consistency of results. The opportunity for consistency in the delineation of seafloor geoforms lends itself well to large regional characterization efforts – especially when classification units and terminology can be implemented consistently through the use of an ecological classification standard such as CMECS.

The landform raster output from BRESS was utilized as the basis to delineate CMECS "Level 1" geoform units for Gosnold Seamount. Level 1 geoforms are defined as generally larger than one square kilometer (FGDC, 2012) and correspond to Megahabitats in the Greene et al. classification system (2007). The raster of landform types was converted to a polygon layer in ArcGIS Pro 2.12 software to enable reclassification of homogenous units. It was necessary to reclassify the flats at the top of the guyot in order to distinguish them from the abyssal flats at the base of the seamount. The results of classifying Gosnold Seamount using CMECS units (existing and proposed) are shown in **Table 2.2** and **Figure 2.4.** Of particular note are the proposals to recognize footslope and shoulder geoforms in the standard. Both of these terms are recognized and defined in terrestrial landscapes by the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, 2018). These geoforms also often have ecological importance in the terrain which make their identification useful. Footslopes are concave areas in the terrain and can form transitional habitats between slopes and flats. Shoulders represent the convex transition zone between steeps and summit flats – areas which have often been found to be biological hotspots on oceanic seamounts where sessile attached fauna take advantage of the combination of exposed hard substrates and food-supplying currents that can occur in these relatively rare topographic areas (see for example NOAA CAPSTONE expedition results in Raineault et al., 2018).

Table 2.2. CMECS geoform classes for Gosnold Seamount as organized by CMECS hierarchical principles of moving to smaller size features and more detail from left to right. Boxes highlighted in grey are provisional units, meaning units that are not part of the standard but proposed for consideration to integrate into the standard in the next formal revision. These proposed units were deemed necessary since the standard lacked comparable existing units for a deep sea seamount.

Tectonic Setting	Physiographic Setting	Geoform Origin	Geoform	Geoform Type
Abyssal Plain	Marine Basin Floor	Geologic	Seamount	Guyot
			Flat	Provisional: Guyot Flat, Provisional: Abyssal Floor
			Ridge	Provisional: Seamount Ridge
			Slope	Provisional: Seamount Slope
			Provisional Unit: Valley	Provisional: Seamount Valley
			Provisional Unit: Shoulder	Provisional: Seamount Shoulder
			Provisional Unit: Footslope	Provisional: Seamount Footslope

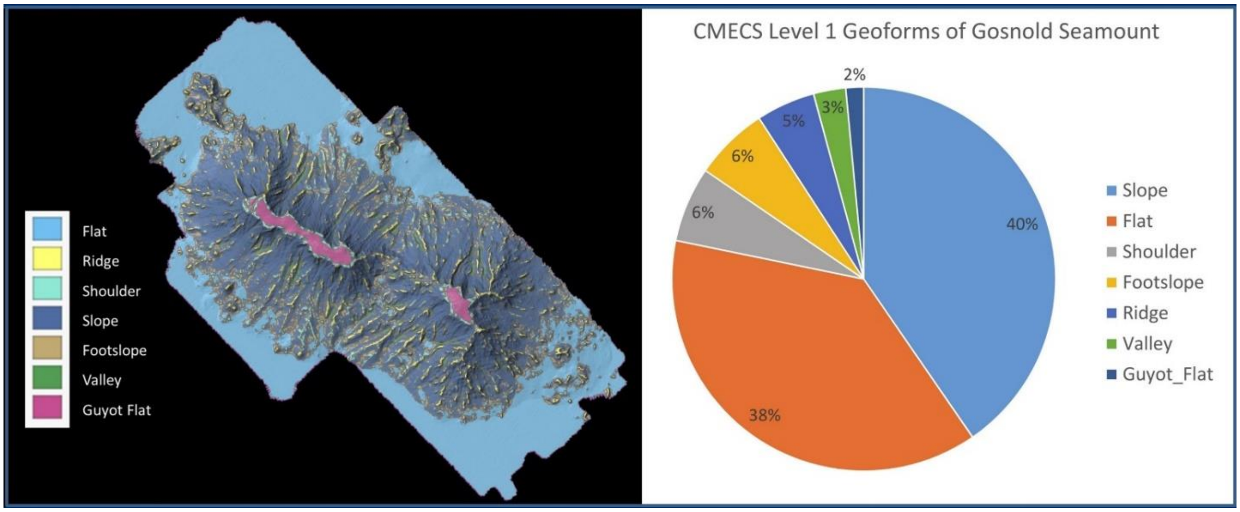

Figure 2.4. Map of geoforms delineated for Gosnold Seamount.

Since the bathymorphon approach to geomorphological classification employs a line-of-sight approach within a search annulus around a DEM node (Yokoyama et al., 2002), it is less sensitive to changes in scale then neighborhood-based methods of terrain analysis employing a fixed search window. However, the minimum and maximum size of the search annulus radii parameters must be set appropriately depending on the scale of the feature that the analyst is seeking to identify within the DEM and the severity of “noise” (small scale artifacts) in the DEM grid. In the DEM analysis of Gosnold Seamount, the results also differed significantly depending on the flatness angle parameter, as this is a key determinant of how slopes and flats are classified. For the Gosnold Seamount with features having slopes approaching vertical in some areas, and a relatively flat summit to the guyot, a flatness angle of 5° was chosen as optimal. The optimal flatness parameter was selected through extensive experimentation with varying angles.

Once the landform mask was created within BRESS, the resulting area kernels were utilized by the seafloor segments algorithms in BRESS as a starting basis for the further segmentation of seafloor facies with similar acoustic backscatter response using the intensity-levels of the pixel from the backscatter mosaic of Gosnold Seamount. By comparing histograms between kernels of the same seafloor landform type (e.g. “ridge”), areas are split or merged depending on the difference or similarity between the textural characteristics of the mosaic pixels associated with each kernel. A distinct segment class therefore represents an area that has been classified with the same landform type and similar reflectivity texture (Masetti et al., 2018). The resulting seafloor segmentation map for Gosnold Seamount is shown in **Figure 2.5.**

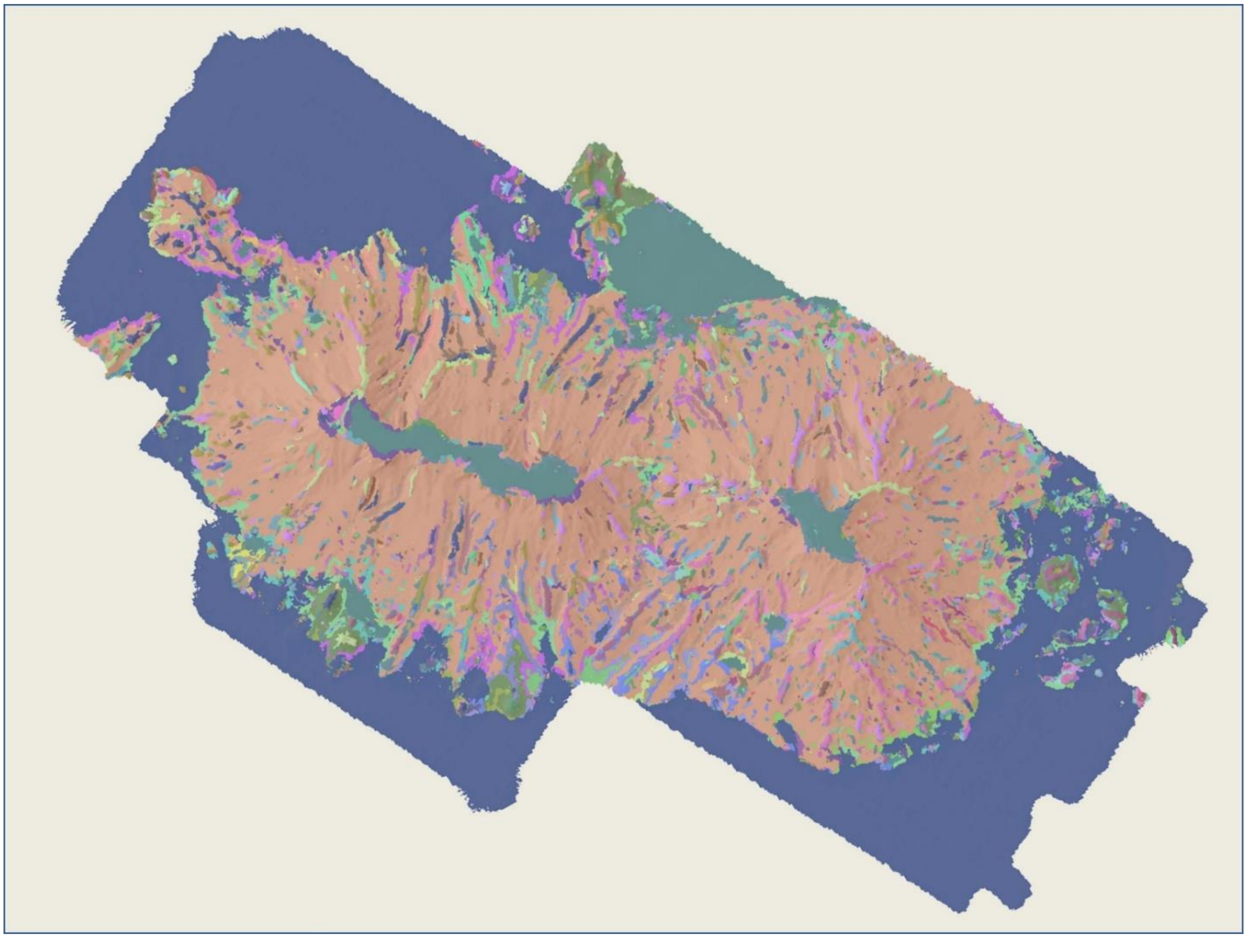

Figure 2.5. Seafloor segmentation map for Gosnold Seamount. Each distinct color represents a segment class with the same landform type and similar reflectivity texture. There are 336 segments in the map, but the majority of the area is dominated by just a few large segments.

Along with the segmentation of seafloor based on landforms and backscatter response texture, BRESS calculates thirteen spatial statistics for each node of the bathymetric grid – the full utility of which were not explored by this study. The output of the segmentation was not used to try to attempt a predictive classification of CMECS substrate types across the entire seamount feature, but does offer potential to be used this way in future research efforts. There was insufficient groundtruth data to attempt to classify substrate types based on backscatter response texture. The identification of common landform types with similar acoustic textural response provides useful guidance on choosing where to gather substrate ground-truth data to aid in interpretation of the backscatter. This would inform either a strategic sampling plan aimed at getting samples thought to be representative of the largest area features on the seamount (i.e. the "biggest bang for the buck") or in planning a more statistically robust stratified random sampling plan. Future work may seek to utilize the segmented areas to conduct theme-based angular range analysis to estimate sediment type from backscatter data, which could then ideally inform predicted CMECS sediment types over large regions of the deep sea.

2.4 Biological Communities

All of the ROV dive video of the seafloor was analyzed manually by a trained researcher at UNH/CCOM in order to create a spreadsheet of 933 georeferenced annotations of organisms and associated substrate types. NOAA OER has developed a set of customized publicly-available Python code scripts (M. Malik, personal communication, 2017) that were used to facilitate the playback and annotation of ROV video integrated with navigation and CTD data files (salinity, temperature, DO). Video imagery, environmental sensor data, and navigation/position data were integrated into a common annotation interface utilizing the shared time stamps associated with each dataset. The annotation tool was customized in order to easily add time/position stamped observations of organisms and substrate type along the ROV dive track. The dominant substrate type over each 50 m segment of the ROV track was also classified using substrate unit terminology from CMECS into four classes: bedrock (10% of ROV track), fine unconsolidated sediments on bedrock (84%), coral rubble (1%), and sand (5%) as shown in **Figure 2.6.** Substrate was classified over 50 m segments to account for the variability in the ROV positioning, and to classify substrate at a scale closer to the resolution of available multibeam sonar bathymetry and backscatter data.

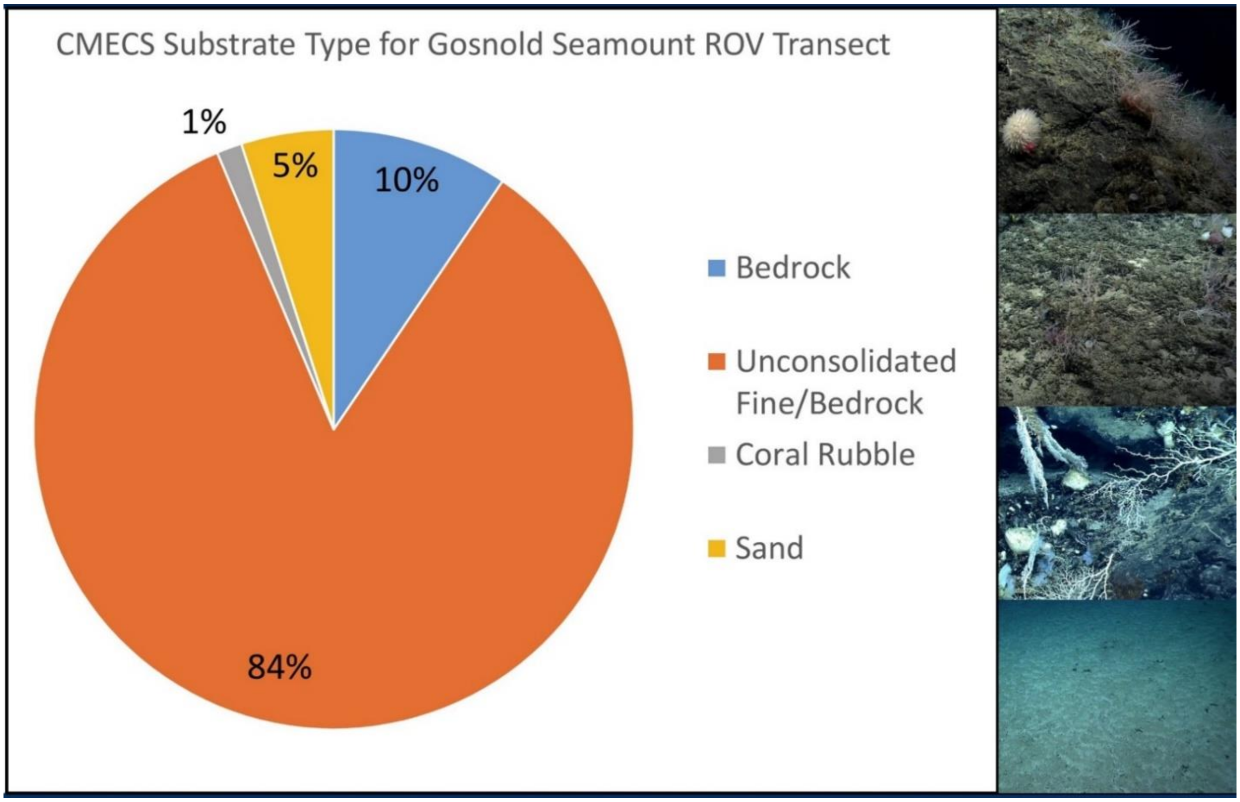

Figure 2.6. CMECS substrate type as characterized over 50m segments of the ROV track. Examples images of each substrate type are shown on the right, following the order of the legend labels.

Organisms were taxonomically classified and counted within an approximately 0.5 m wide strip in front of the ROV for each segment of the track in which lasers were visible. The lasers are 10 cm apart, and the analyzed strip included the area between the lasers as well as 20 cm on each side of the lasers. Organisms were identified to the lowest possible taxon or morphotype using the recorded (auditory and written) events log captured for each dive. Identification of organisms were conservative given that identifications were made based on video imagery without the benefit of voucher specimens. Identifications ranged from class to genus level. Organisms from the phylum Echinodermata and Porifera were identified to class. Cnidarians were identified to genus with the exception of anemones which were identified to order and coral that could not be identified. Eleven genera of corals, 2 classes of sponges and 4 classes of echinoderms were observed along the track (**Figure 2.7**).

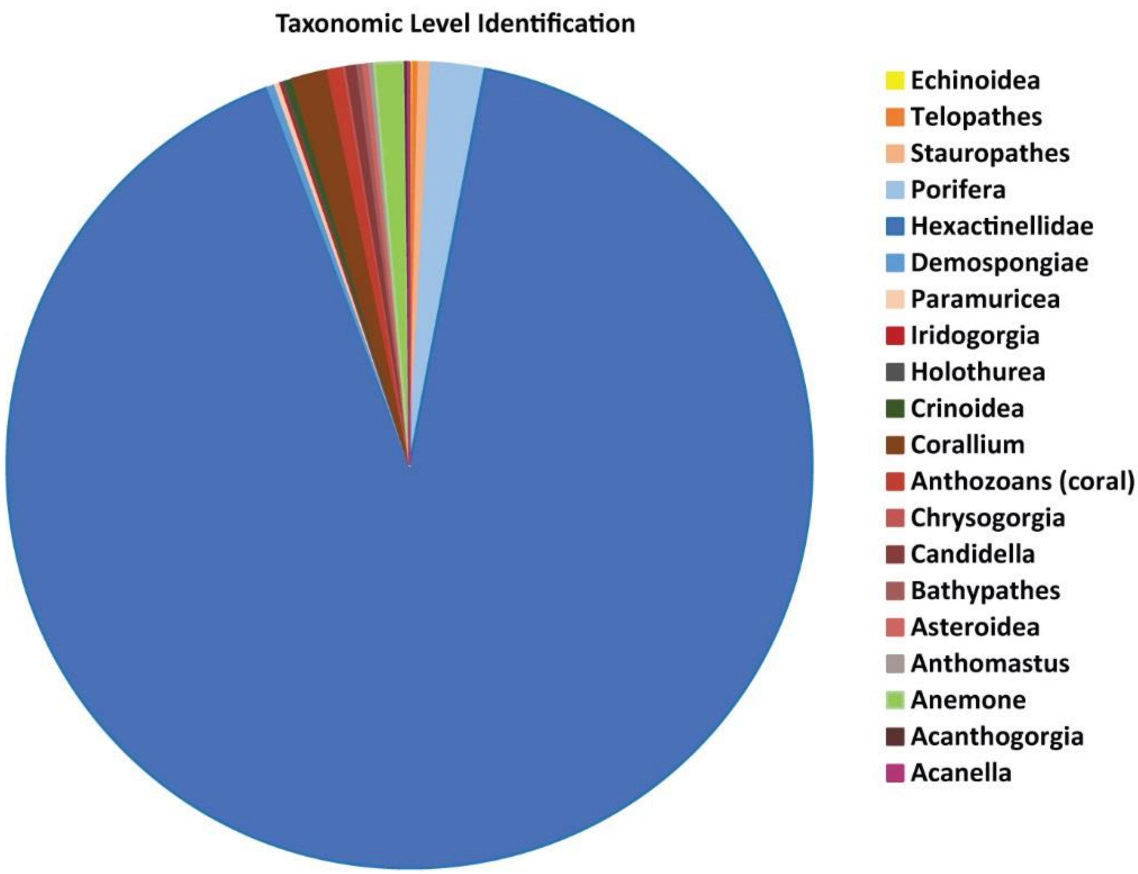

Figure 2.7. Taxa identified along the ROV track on Gosnold Seamount as represented by percent of overall counts within 0.5 m wide strips for each segment of the track in which lasers were visible. Counts were heavily dominated by Hexactinellidae (glass sponges).

As the relative importance of factors that control species distribution changes with scale (McGill, 2010), the interaction between factors and their effect on the distribution of assemblages was analyzed at different scales. The georeferenced annotated spreadsheet was the basis for the first (fine) scale analysis. Corals, sponges and environmental factors were pulled out of the annotation file and a nominal logistic regression was used to determine which factors affect their distribution. This fine-scale analysis used deep water corals and sponges as they are habitat forming and were the most common groups of organisms along the track. Biological assemblages were classified utilizing CMECS units as follows: glass sponge reef, mixed colonized deep-water reef, coral colonized deep-water reef, and few/absent biota (**Figure 2.8**).

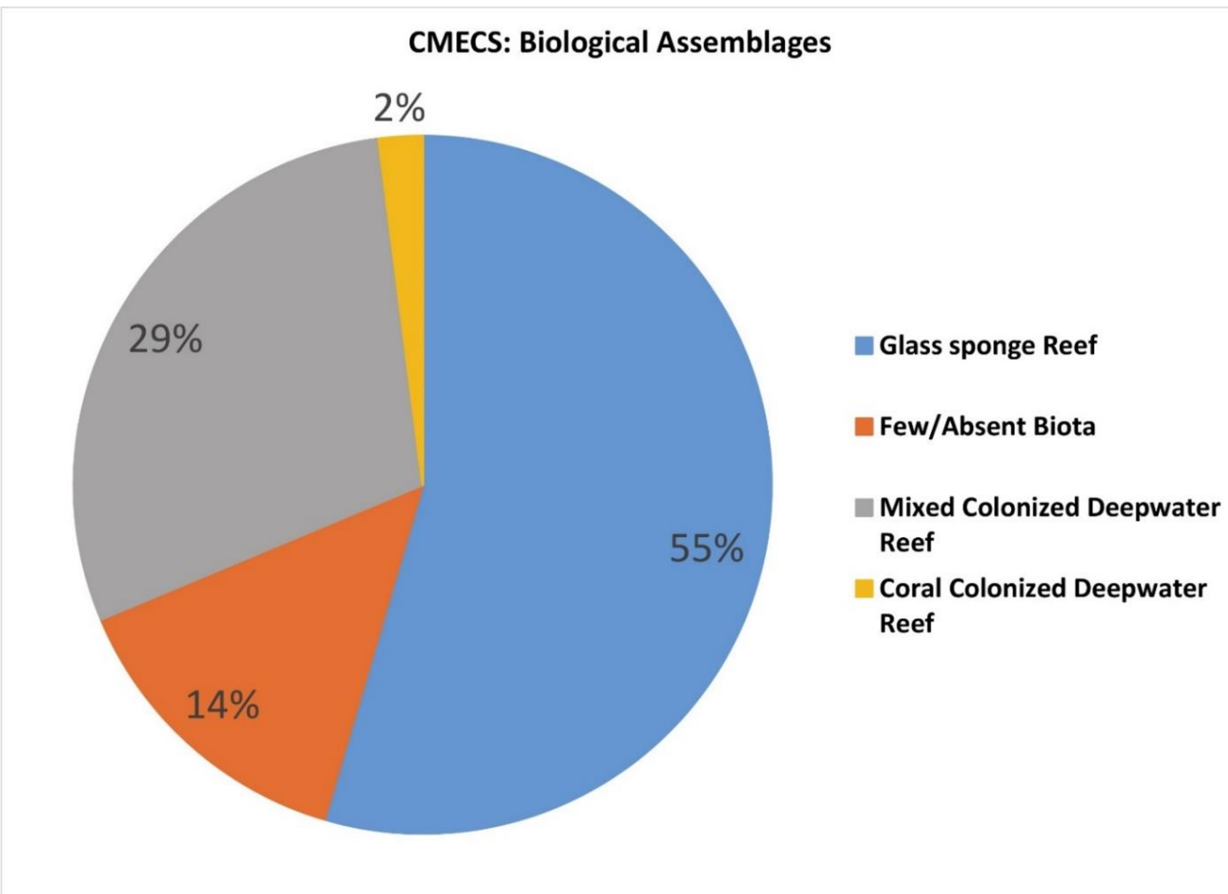

Figure 2.8. CMECS biological assemblage types per 50m segment of ROV track, as a percentage of all of the 50m segments in the track. Glass sponge reef made of the majority of the track (55%), followed by mixed colonized deep-water reef (29%).

2.5 Surrogacy

Biotic and environmental matching (BEST method from Clarke and Gorley, 2008) was used to obtain the optimum environmental variables (temperature, depth, salinity and dissolved oxygen, slope and sediment type) that characterized biological assemblage types (mixed, glass sponge dominated, coral dominated and few/absent biota) identified in 50 m segments (224 segments in total of which 54 were suitable for analysis because ROV lasers were turned on for scale). In contrast to the annotated file, CTD data were averaged for each 50 m segment. Bray-Curtis indices of similarity based on abundance data were calculated between mixed, coral dominated, sponge dominated, and “no epifauna” classes. Assemblage classification of segments was performed using hierarchical cluster analysis based on a Bray-Curtis similarity matrix created from untransformed abundances. This application groups segments that have similar taxonomic composition. A Similarity Profile Test (SIMPROF) was used to determine significant differences in faunal composition among segments. Discriminator species for each segment class were determined using the SIMPER statistic (SIMilarities PERcentages from Clarke et al., 2008). Discriminator species were calculated by first computing the average similarity in species composition within segments (Clarke, 1993). The overall average similarity was then broken down into separate contributions from each species. To classify assemblages in segments without lasers, faunal composition was visually classified and placed into existing classified segments based on the cluster analysis, or into a new unique segment classification if observed to be different from existing classes. Assemblage analyses were generated using Primer 6.0 (Primer-E Ltd. Plymouth, UK).

Nominal regression revealed that depth, temperature and sediment type were significant predictors of individual coral along the ROV track ($p < 0.001$, $p < 0.001$, $p < 0.001$, respectively). In contrast, slope, sediment type and dissolved oxygen were significant predictors of sponge distribution along the track ($p < 0.0001$ for all). Results of the nominal regression were evaluated at a conservative significance level of 0.01. Correlations of depth and sediment type were found to significantly correlate with glass sponge assemblages ($R = 0.113$, $p = 0.04$, $n = 121$) while depth and temperature were found to significantly correlate to segments with few or no organisms ($R = 0.749$, $p = 0.03$, $n = 31$). No significant correlations were found between environmental variables, mixed ($p = 0.056$) and coral dominated assemblages ($p = 0.10$). There was a negative correlation between glass sponges and depth, with higher densities of glass sponges within segments occurring at shallower depths and lower dissolved oxygen.

The fine-scale analysis allowed for the most direct comparison of organism occurrence with abiotic variables, while the broader scale analysis (based on 50 m segments) did not reveal correlations between biotic and abiotic variables. This is likely due to the variability of environmental conditions and sediment type along a segment that is not well captured over the 50 m scale. Interestingly, deep sea corals captured the attention of viewers and annotators of the ROV video data but were not the dominant group based on abundance. This underscores the importance of quantitative analysis of the biology imaged in the video versus less robust qualitative observations and annotations of the marine habitat surveyed.

In summary, the application of CMECs to Gosnold Seamount provided a useful systematic framework for structuring geoform, substrate, and biotic classification of benthic habitat. Using this standard, in combination with the semi-automated seafloor segmentation approach utilized, can provide a consistent and reproducible habitat classification approach for large regions and facilitate comparison of habitats among features. New provisional units not currently in CMECS were deemed necessary for proper description of major seamount geomorphic features and are proposed for potential adoption in the next update of the standard. Substrate classes available in the standard worked well to characterize substrates observed in the ROV video data. Delineation of geoforms and segmentation of the backscatter data offers a promising analytical approach to guide additional exploration, sampling, and characterization of substrates and habitats.

Chapter 3

Standardized Geomorphic Classification of Seafloor Within the United States Atlantic Canyons and Continental Margin

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Abstract

Accurate seafloor maps serve as a critical component for understanding marine ecosystems and guiding informed ocean management decisions. From 2004-2015, the Atlantic Ocean continental margin offshore of the United States has been systematically mapped using multibeam sonars. This work was done in support of the U.S. Extended Continental Shelf (ECS) Project and for baseline characterization of the Atlantic canyons, but the question remains as to the relevance of these margin-wide data sets for conservation and management decisions pertaining to these areas. This study utilized an automatic segmentation approach to initially

identify landform features from the bathymetry of the region, then translated these results into complete coverage geomorphology maps of the region utilizing the Coastal and Marine Ecological Classification Standard (CMECS) to define geoforms. Abyssal flats make up more than half of the area (53%), with the continental slope flat class making up another 30% of the total area. Flats of any geoform class (including continental shelf flats and guyot flats) make up 83.06% of the study area. Slopes of any geoform class make up a cumulative total of 13.26% of the study region (8.27% abyssal slopes, 3.73% continental slopes, 1.25% seamount slopes). While ridge features comprise only 1.82% of the total study area (1.03% abyssal ridges, 0.63 continental slope ridge, and 0.16% seamount ridges). Key benefits of the study's semi-automated approach include computational efficiency for large datasets, and the ability to apply the same methods to large regions with consistent results.

3.1 Introduction

Between 2004 and 2015, a vast region of the Atlantic Ocean margin adjacent to the east coast of the United States - from the continental shelf break to the abyssal ocean, from Canada to Florida – was systematically mapped using multibeam sonars, collecting both bathymetry and backscatter data (Armstrong, et al., 2012; Calder, 2015; Calder and Gardner, 2008; Cartwright and Gardner, 2005; Eakins et al., 2015; Gardner, 2004; Lobecker et al., 2011, 2012, 2014, 2015, 2017, 2019; Malik et al., 2012; McKenna and Kennedy, 2015; Sowers et al., 2015; Sowers and Lobecker, 2019). This work was done in support of the U.S. Extended Continental Shelf (ECS) Project (U.S. Extended Continental Shelf Project, 2020) and for baseline characterization of the submarine canyons in this region.

The unprecedented detail and complete coverage of these multibeam sonar data sets has enabled new insights into the distribution of submarine landslides (Twichell et al., 2009), the tsunami hazard potential of the Atlantic Margin (ten Brink et al., 2014), submarine canyon morphology (Brothers et al., 2013a), and the apparent relationship between canyon catchment area and sediment flow dynamics (Brothers et al., 2013b). However, the question remains as to the relevance of these margin-wide bathymetry and backscatter data sets for conservation and management decisions pertaining to these areas. This study utilizes one aspect of these data (bathymetry) to generate broad scale continuous coverage geomorphology maps as a key component of marine habitat characterization in support of ecosystem-based management of the ocean.

Broadly speaking, geomorphology is the study of the physical features of the surface of the earth (or other planets) and their relation to its geological structures (Stevenson, 2010). Seafloor geomorphology is a first-order expression of geologic processes that create benthic habitats. Harris (2012) insightfully articulated three broad categories of spatial seafloor classification (geomorphology, seascapes, and predictive habitats), representing a continuum of characterization as managers move from data-poor to data-rich circumstances. Therefore, classifying geomorphology serves as a fundamental step in translating bathymetry into value-added spatial data of use for ocean managers, and a primary basis for generating seascape maps and informing predictive habitat models. Maps of seafloor geomorphology directly support marine spatial planning, including applications in protected area designation, offshore infrastructure siting, geohazard assessment, habitat research, and environmental monitoring (Micallef et al., 2018).

Evaluating the usefulness of seafloor geomorphology as a proxy for characterization of complex benthic biological communities is an active area of global marine research effort (Harris and Baker, 2011; Althaus, 2012). While many useful studies have been completed on this topic, methods applied in one study area are typically challenging for other researchers to replicate in other regions of interest. When the delineation and classification of geomorphology is based solely on subjective expert opinion, results are difficult to duplicate by other scientists and the classification rules may only be readily applicable to specific regions. Thus, an important trend in this field of research is the development of approaches that take advantage of the computational power and the objectivity and reproducibility of automated digital terrain analysis tools (e.g., Walbridge et al., 2018). With proper documentation, these tools also provide the benefit of reproducible analytical workflows and the generation of comparable results over large regions. This outcome is becoming even more important as the global ocean exploration community is making commitments towards mapping the entirety of the Earth's deep sea by 2030 (Mayer et al., 2018), and interpreting the results in support of sustainable ocean management. Harris et al. (2014) produced the first digital global geomorphology map of the ocean generated using a combination of automated and expert judgement methods applied to the SRTM30_PLUS global bathymetry grid (Becker et al., 2009) reduced to a uniform grid spacing of about 1 km. The present study utilizes a terrain analysis approach based on the identification of bathymorphons (Jasiewicz and Stepinski, 2013; Masetti et al., 2018) in order to semi-automate the classification of landforms from a bathymetric terrain model with 100 m grid resolution covering a vast expanse of deep ocean seafloor off the east coast of the United States and Canada.

An emerging trend in the field of marine habitat characterization is the development and application of standardized classification schemes (e.g., EEA, 2004). A "common language" of terminology in describing seabed features is necessary if spatial datasets from a variety of sources are to be synthesized into coherent products useful to ocean managers, researchers, and policy makers. The benefits of standardized classification schemes become particularly important when synthesizing marine habitat information at the regional level covering many marine datasets and management jurisdictions. Harris (2012a) provided a review of standardized hierarchical marine classification schemes utilized by different nations, and noted that direct comparisons among them are difficult given that they have been derived from varying information sources and intended for application to different environments. In the United States, the Coastal and Marine Ecological Classification Standard (CMECS) was developed as a framework for organizing data about the marine environment so that ecosystems can be identified, characterized, and mapped in a standard way across regional and national boundaries (NOAA, 2015). The purpose of this study was not to evaluate the merits of different classification schemes, but rather to test and refine the application specifically of the CMECS standard to a deep sea environment largely within U.S. management jurisdiction.

CMECS is a hierarchical classification scheme that enables the user to characterize the marine environment utilizing separate "components" – major topical themes that describe the water column (water column component), the geomorphology of the seafloor (geoform component), the substrate of the seafloor (substrate component), and the biology of an area (biotic component). Each of these components has its own hierarchical structure and catalog of defined classification units. Thus thoroughly characterizing a cube of the three-dimensional marine environment could involve all four components. Each of these components can also be utilized independently of each other and used to generate separate spatial datasets. This paper focuses solely on the application of the CMECS geoform component. This work is envisioned as a fundamental piece of the larger holistic characterization of the marine seascape for the Atlantic margin offshore of the United States.

Application of CMECS to deep sea habitats is still in the early phases of testing and adoption. As a dynamic content standard, CMECS incorporates the use of provisional units, which allow researchers to add proposed new units to the standard as they are discovered. This flexibility is especially valuable in the deep sea, where knowledge is increasing rapidly and new discoveries are commonplace in these poorly-studied habitats. The current study developed methods to map the CMECS geoform component (geomorphology) in a repeatable way that could also be applied to other regions. This study demonstrates the application of both a semi-automated approach to delineating and classifying seafloor geomorphologies, and the application of a standardized terminology to describe these “geoforms” as consistent with the framework provided by CMECS.

The study region was selected to examine how broad scale multibeam sonar data specifically collected to support extended continental shelf studies can be further interpreted to provide value for ecosystem-based management purposes. It is important to note that within this paper, the terms continental shelf, continental slope, and continental rise and distinctions between them, are not being used in the context of Article 76 of the United Nations Convention of the Law of the Sea (UNCLOS) and thus should not be taken as representative of any U.S. position on the location of these boundaries. UNCLOS specifies the formulas a nation must use to delineate the continental shelf beyond 200 nautical miles for juridical purposes, unrelated to ecological processes or classification. This study used different criteria, based on professional judgement that met the study purpose of segmentation of the seafloor for application of an ecological classification scheme (CMECS) that has different classification decision rules from those applied under UNCLOS.

3.2 Materials and Methods

3.2.1 Study Area and Input Datasets

The study area covered by this analysis includes the continental slope/rise and abyssal plain of the Atlantic Ocean east of the continental shelf of the east coast of the United States and Canada. Depths in the study area range from 72m near the edge of the continental shelf break to a maximum depth of 5435m in the abyssal plains. Mapped areas included in the study extend beyond the existing 200 nautical mile (nm) maritime limit of the U.S. Exclusive Economic Zone (EEZ). The northern limits of the study area are at latitude 43° 47.8N offshore of Canada, and the southern limits of the area are at latitude 28°18.8N offshore from the U.S. state of Florida. The mapped area is 959,875 km^2 (well over twice the size of the state of California).

The primary input dataset for the analysis was a digital terrain model generated via synthesis of the highest quality bathymetric data publicly available within the study region. The synthesis incorporates data from 28 separate cruises (Johnson, 2020). The vast majority of bathymetry data used in the synthesis grid originated from Extended Continental Shelf expeditions led by CCOM/JHC on several research vessels and on ocean exploration expeditions led by NOAA's Office of Ocean Exploration and Research on the NOAA vessel *Okeanos Explorer*. Data were also incorporated from mapping surveys conducted by other vessels. All of the source data used in the analysis is available via the NOAA National Centers for

Environmental Information multibeam archives (NCEI, 2004). This bathymetry grid was created as part of the U.S. and Canadian Extended Continental Shelf efforts and is available on a public internet map server hosted by the University of New Hampshire's Center for Coastal and Ocean Mapping / Joint Hydrographic Center (CCOM/JHC) (Johnson, 2020).

Bathymetry for the deeper regions of the study area (generally deeper than 2000m) were collected as part of the U.S. Extended Continental Shelf (ECS) Project by CCOM/JHC. Data were collected on eight different cruises between 2004-2015, using 12-kHz, Kongsberg EM120 or EM122 multibeam sonars. Data were acquired with the initial purpose of supporting the determination of the outer limits of the U.S. juridical continental shelf consistent with international law.

Shallower bathymetry data that cover the shelf break and Atlantic canyons out to depths of the coverage of ECS cruises were collected for the National Oceanic and Atmospheric Administration (NOAA) Atlantic Canyons Undersea Mapping Expeditions (ACUMEN) Project using NOAA vessel Okeanos Explorer. Data were collected during nine different cruises using a 30-kHz Kongsberg EM302 multibeam sonar on the Okeanos Explorer between 2011-2014.

Data were synthesized into the bathymetric grid using WGS84 spatial reference and projected with the Lambert Conformal Conic projection with a grid resolution of 100 m, as shown in **Figure 3.1**. The grid was generated using the weighted moving average gridding option in QPS Qimera software with a 3x3 moving window algorithm that fills small holes in the bathymetry and slightly smooths the overall surface. However, the underlying bathymetric data is very close to 100% full coverage at the 100m resolution of the grid, and interpolated depth values are essentially negligible as a percentage of the study area mapped.

Data quality was validated for the mapping cruises that generated the data used in the synthesis by the calibration of multibeam mapping systems, professional ocean mapping experts overseeing all aspects of the surveys, regular frequent sound velocity profiles of the water column, rigorous cleaning of noise and erroneous soundings following raw data collection, and cross-line validation analysis of survey areas. The synthesis of multibeam sonar data was compiled and quality controlled by an expert from the UNOLS Multibeam Advisory Committee (Johnson, 2020; Multibeam Advisory Committee, 2019). Specifics on data quality control and validation can be found in the individual publicly available cruise reports for each cruise.

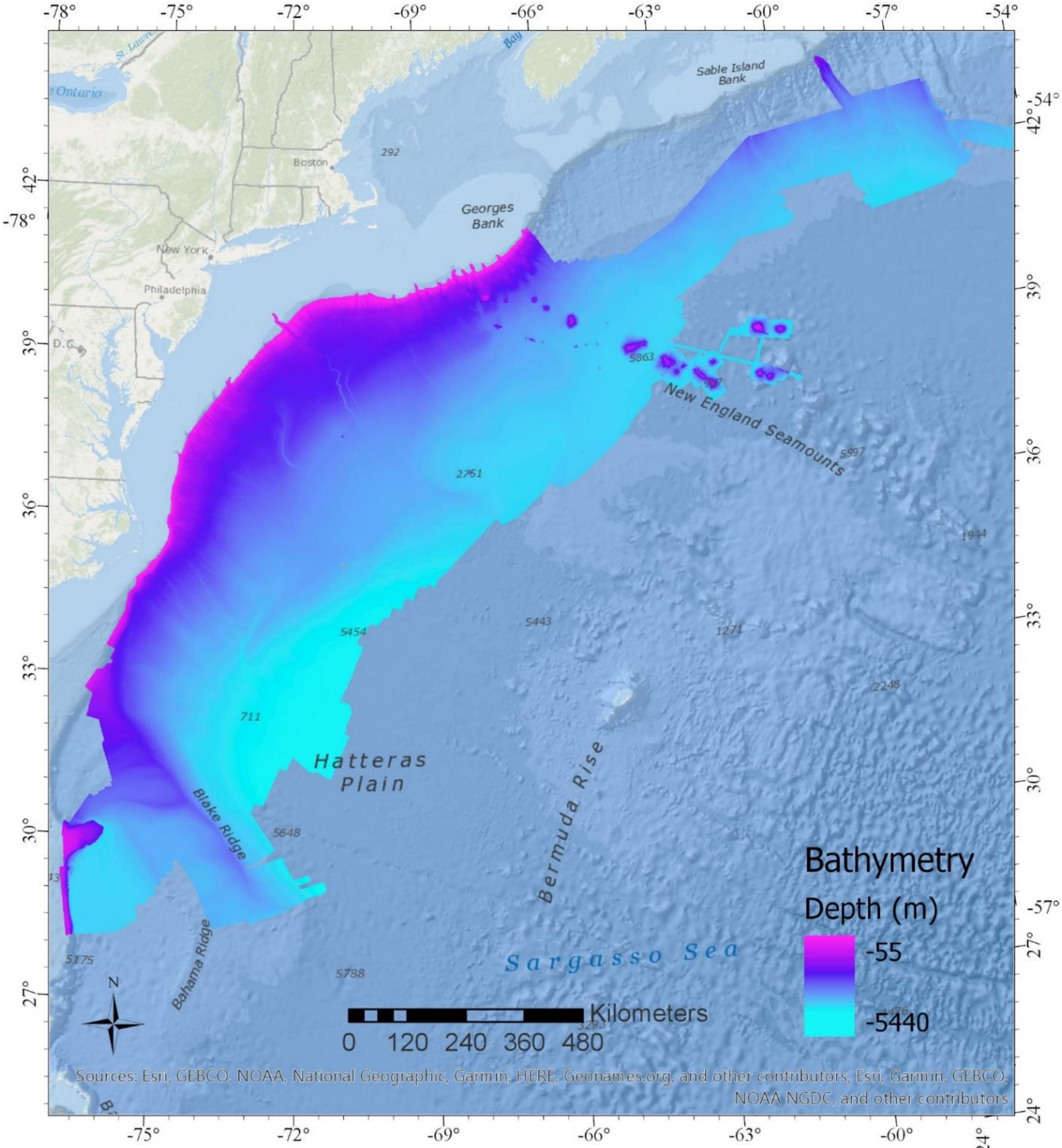

Figure 3.1. Bathymetric synthesis terrain model grid of the U.S. Atlantic margin study region used as the primary data source input into the study.

The analysis of the bathymetric terrain model of the study area utilized the Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation (BRESS) method developed by

Masetti et al. (2018). This tool is a free stand-alone application available at https://www.hydroffice.org/bress/main (Hydroffice, 2019). The BRESS analytical approach implements principles of topographic openness and pattern recognition to identify terrain features that can be classified into easily recognizable landform types such as valleys, slopes, ridges, and flats. These “bathymorphon” architypes represent the relative landscape relationships between a single grid node and surrounding grid nodes as assessed in eight directions around the node. The position of a grid node relative to others in the terrain are determined via a line-of-sight method looking out in each direction by a user defined search annulus specified by an inner and outer search radius. Details on this approach to geomorphic terrain analysis can be found in Jasiewicz and Stepinski (2013).

3.2.2 Interpretation of Seafloor Landforms

An important distinction between this method and many other terrain analysis algorithms is that the identification of landform elements between a grid node and eight directions around it self-scales to adjacent features, whereas many terrain analysis algorithms work using a fixed neighbourhood “moving window” approach (Jasiewicz and Stepinski, 2013). The grid neighbourhood approach will identify fine features with a small cell window frame, and larger features with a bigger window, while the geomorphon approach has the capacity to capture both scales to some extent (within the limits of a defined search annulus). This is because it calculates elevation values (using both zenith and nadir angles) between the grid node and the maximum change in height of surrounding features (positive or negative) via a “line-of-sight” approach.

The BRESS algorithm was used to identify bathymorphon patterns in the bathymetric surface, generate area kernels (aggregations of the same bathymorphon type) and then utilizing a look-up classification table, these patterns were translated into landform types. The original geomorphon work (Jasiewicz and Stepinski, 2013) proposed a ten-type landform classification: flat, peak, ridge, shoulder, spur, slope, pit, valley, footslope, and hollow. BRESS introduced a simplified six-type landform classification (flat, ridge, shoulder, slope, valley, and footslope) and, recently, a minimalistic classification (flat, ridge, slope, and valley). The simplest classification was determined to be the best choice for the extremely large study area in this case, resulting in the creation of a continuous landform map of the Atlantic margin region comprised of four classes: flat, slope, ridge, and valley.

Key user defined parameters in the landforms analysis tool within BRESS are the inner and outer radius of the search annulus and the flatness parameter. If the inner radius is set too small, results can be negatively impacted by noise near the grid node (e.g., multibeam sonar surveying sound velocity offsets or outer beam “striping” artifacts in the bathymetry grid). The search annulus units are grid nodes, so the length of this is dependent directly on the resolution of the input raster grid. Alternatively, the user may specify the search radius parameters in meters. Reasonable values for the search annulus are fairly intuitive to a skilled analyst and are informed primarily by the scale of the features one is seeking to detect and the resolution of the bathymetric grid. The default parameters of inner/outer radii of 5/10 grid nodes respectively work well for many terrains. For this study extensive testing of the parameters on different regions of the grid revealed that an inner radius of 3 grid nodes and an outer radius of 15 grid nodes resulted in the delineation of landform features most comparable to what would be manually classified by a skilled analyst. These values were determined by varying the inner and outer radius parameters of the model and draping the automatically classified landform spatial layers over the bathymetry for examination within 3D visualization software (QPS Fledermaus).

An inner radius of 3 nodes was larger enough to ignore “noise” artifacts in the bathymetry that could be mistaken as features, while still enabling finer scale geomorphic features to be classified. The outer radius of 15 nodes enabled classification of larger scale geomorphic features of interest. The results were then evaluated to determine if delineations among landforms aligned with logical topographic feature breaks and to assess if the key morphologies of interest in the terrain (in this case ridges, slopes, valleys, and flats) were identified. Separate manual landform classification maps were not generated in this study for direct comparison with the automatic classification results, as they would be as equally subjective as the methodology used and therefore offer limited additional insights. The bathymetric grid used in this study was 100m resolution, so the inner search radius was equal to 300m and the outer radius was equal to 1500m.

Results of the landforms analysis are sensitive to the choice of flatness parameter. A flatness number that is too large will result in low to moderate relief seafloor features being classified as “flat”, and too small of a number will result in excessive “slope” results. This parameter was tested extensively in both the steep terrains (continental canyons and seamounts) and low relief terrains (e.g., abyssal plain) found in the study region. Testing results determined that one flatness parameter could not yield useful results for the entire region. It was determined that the extremely steep seamounts needed a flatness parameter of 5.0 degrees, the continental slope region of the margin needed a flatness parameter of 3.0 degrees, and the low gradient regions of the Blake Ridge and abyssal plains needed a flatness parameter of 1.0 degree. In order to apply the necessary variable flatness terrain values to the bathymetry, a separate spatial layer mask was created using the masking tool in BRESS, then applied to compute landforms (**Figure**

3.2). This flatness angle mask spatial layer was generated manually via interpretation of the logical bathymetric breaks among the continental slope, abyss, and seamount features.

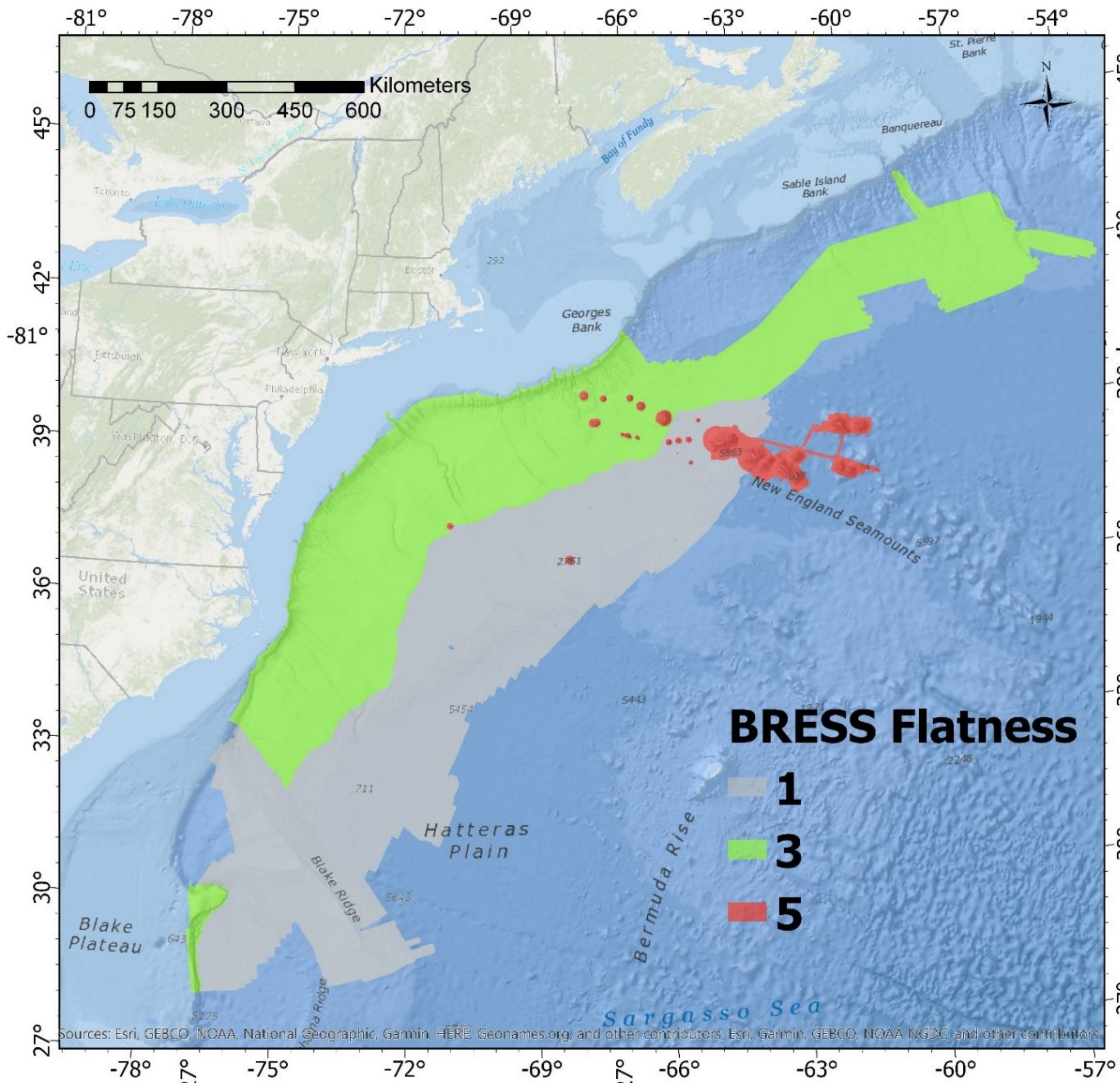

Figure 3.2. Flatness parameter mask used to apply different flatness values of the BRESS landform algorithm to different regions of the Atlantic margin study area. Parameter of 5.0 degrees (red) applied to the seamounts, 3.0 degrees (green) applied to the continental slope, and 1 degrees (gray) applied to abyssal areas. ESRI ocean base layer shown in the background for context.

The initial output of the landforms classification identified most of the prominent landform features of interest in both high and low relief areas of the study region. However, within low relief areas, a limited number of linear artifacts from the outer beam striping typical of multibeam sonar mapping systems were visible and easily discernible from real seafloor features. These small artifacts were minor and typical of the increased uncertainty of soundings in the outer beams of multibeam sonars, and were not the result of any interpolation of the original underlying dataset. Given the low flatness parameter applied to abyssal areas, the larger bumps in the outer swath sectors of multibeam in a few isolated areas were classified by BRESS as small landforms other than flats. These classification artifacts occurred in small select regions of the overall abyssal region of the grid, and were manually reclassified to flats via the application of a user-generated mask. This targeted manual quality control of the landform classification output was completed via visual inspection of the landforms draped on the bathymetric grid, and areas were corrected by encircling in a polygon using the masking tool within the BRESS software. While not an automated process, this tool provides a quick and effective quality check to improve the appearance and quantitative results of the analysis over survey areas subject to limited systematic artifacts from multibeam sonar surveys.

The output from the BRESS landform tool is either an ASCII Grid file or a geotiff image that can be imported into any spatial analysis or visualization software that can read these formats. The resolution of the output ASCII exactly matches the resolution of the input bathymetry file, in this case 100m. The ASCII file consists of raster cells with code values that represent the landform designation of the nodes in the grid. In this case there were four code values representing each of the four landform classes derived from the lookup table in BRESS: 1 for flats, 3 for ridges, 6 for slopes, and 9 for valleys.

3.2.3 Conversion of Landform Units to CMECS Geoform Units

The landform raster output from BRESS (a grid file in ASCII Grid format) was imported into ArcGIS Pro v2.6.0 for additional analysis and conversion of landform units into CMECS geoform units. Landform units were modified to delineate CMECS geoforms using decision rules based on existing CMECs standard definitions of units. CMECS provides a catalog of units for geoform classification, along with definitions of each unit class in the standard document (FGDC, 2012). Since CMECS is intended to be a dynamic content standard, the user is able to propose “provisional units” if the existing units do not adequately meet classification needs. This study proposes one new geoform called “valley” (not to be confused with the existing CMECS term “submarine canyon” which is a specific type of valley as explained later) and six new geoform types that are intended to describe specific types of geoforms unique to deep sea features (**Table 3.1**).

Table 3.1. CMECS geoform classes mapped within the Atlantic margin study area. Note that the CMECS classification hierarchy moves towards smaller sized features moving to the right within the columns. Classes noted as "provisional" (grey) are not yet part of the CMECS standard, but were used in this study and are recommended for adoption. A map of the final geoform types from this table is shown in **Figure 3.11**. Units in column 6 show the names of the classification units assigned to the geoform maps presented in this study (mapped units). Most of the units in column 6 are not defined specifically in the Geoform Type hierarchy level of CMECS, but are implicit in the upper level classification (for instance a ridge geoform located on a continental slope is mapped as a Continental Slope Ridge as the geoform type). The term "Abyssal" was used in this column instead of "Marine Basin Floor" as it was deemed more descriptive.

	Tectonic Setting	**Physiographic Setting**	**Geoform Origin**	**Geoform**	**Geoform Type (Mapped Unit Name shown in study maps)**
Shelf	Passive Continental Margin	Continental Shelf	Geologic	Flat	Continental Shelf Flat
Continental	Passive Continental Margin	Continental Slope	Geologic	Flat	Continental Slope Flat
				Ridge	Continental Slope Ridge
				Slope	Continental Slope Slope
				Provisional: Valley	Continental Slope Valley
Abyssal	Abyssal Plain	Marine Basin Floor	Geologic	Flat	Abyssal Flat
				Ridge	Abyssal Ridge
				Slope	Abyssal Slope
				Provisional: Valley	Provisional: Abyssal Valley
Seamount	Abyssal Plain	Marine Basin Floor	Geologic	Seamount	Guyot Pinnacle Seamount
				Flat	Provisional: Guyot Flat
				Ridge	Provisional: Seamount Ridge
				Slope	Provisional: Seamount Slope
				Provisional: Valley	Provisional: Seamount Valley

Landform classes were converted to CMECS geoforms primarily by re-naming them as appropriate for the marine setting in which the units occurred throughout the extent of the Atlantic margin. While landform units can be thought of as the primary building blocks for the identification of larger geomorphic seafloor features (e.g., canyon complexes, sand wave fields) it is proposed here that they also have value in many cases for direct translation into classified geomorphic features. This assertion is based on the fact that the landform features identified for the study area largely fit well within the existing geomorphic classification scheme being applied (CMECS). As apparent from **Table 3.1**, the landform types “flat”, “ridge”, and “slope” are also existing geoform units within CMECS. So a direct translation from landforms to geoforms for these cases was logical.

Although existing CMECS units worked well for direct translation of some landforms, other terms that are useful are not yet part of the standard. For instance, valley features were evident in all of the major study regions evaluated (continental shelf, abyssal plain, and seamounts), but the concept of a valley feature in the deep sea is absent from CMECS. CMECS currently has Submarine Canyons (Physiographic Setting), Shelf Valleys (Level 1 geoform), and Channels (Level 1 and 2 geoforms). None of these classification terms are adequate descriptors for all of the valleys observed in deep sea environments. While certainly some of the valley features on the continental slope and on seamounts and guyots could be called “submarine canyons,” there are many valley features in these areas identified as valleys in the landform analysis which are not submarine canyons. Fortunately, CMECS was designed to be a dynamic content standard subject to user refinement and open to proposals for formal future modifications. Users are advised to designate “provisional units” for classes that are deemed useful but absent from the current version of the standard. Therefore, this study designated the term “valley” as a provisional geoform unit for now (column 5 in **Table 3.1**), and then defined provisional geoform type units (another step down in the classification hierarchy, column 6 in **Table 3.1**) to describe the specific types of valleys occurring within the context of different features in the deep ocean (continental slopes, abyssal areas, and seamounts).

CMECS currently lacks geoform terms that adequately describe the geomorphology of features found within seamount features. Seamounts as entire features are covered by the standard, as there is a Seamount geoform unit and both Guyot and Pinnacle Seamount geoform types defined. It is proposed that adding Guyot Flat, Seamount Ridge, Seamount Slope, and Seamount Valley would be useful unit additions to the standard. These units are shown as provisional units in Table 1. Seamounts have been demonstrated to be hotspots of biological diversity in the deep sea. Ocean exploration ROV dives on seamounts have found that ridge features and the edges of guyots can support dense and diverse aggregations of deep sea corals and sponges, where sessile attached fauna take advantage of the combination of exposed hard substrates and food-supplying currents that can occur in these relatively rare topographic areas (see for example NOAA CAPSTONE expedition results in Raineault et al., 2018).

It is important to note that this study did not classify and map geoforms that are composed of a complex aggregation of landforms. For instance, a submarine canyon is an important feature to map and identify along continental margins, and a CMECS geoform descriptor exists for this feature. However, a typical manual delineation encircling a complete canyon system would encompass the following separate landform types: a channel at the bottom of the valley (thalweg), the steep valley walls, and the ridges on the tops of the slopes. Therefore, this single geomorphological unit is composed of valley, slope, and ridge landforms - refer to Harris et al. (2014) for example. Complex submarine canyon systems contain many of these features, as well as flats and more complex landforms not part of the current scheme (e.g., pits, peaks, shoulders, etc.). Also, since the purpose of this study was to demonstrate what can be done via semi-automated terrain analysis tools over very large regions, manual delineation of these more complex morphologies was not attempted.

CMECS is structured with “physiographic setting” high up in the hierarchy in order to discriminate between continental shelf, continental slope, abyssal plain, and seamount features. Therefore, it was necessary to spatially delineate the study region into these categories. This delineation was done by using the flatness mask ASCII grid which was developed during landform modeling, as it was driven directly by the need to apply different flatness parameters to the continental slope, abyssal plain, and seamount regions. The mask was modified for the region offshore of Canada, as this region was mostly deep abyssal plain for the purposes of geoform classification, but was originally given the flatness parameter applied to the continental shelf due to the need to minimize classification of significant multibeam artifacts. While the term “continental rise” is a physiographic setting term in CMECS, it was not used in the study. This was because the Atlantic Margin has a gradual slope in many areas that makes it challenging to discriminate between a continental slope and a continental rise, and if present, a flattening out in gradient did not appear to occur until depths of 4000m at the shallowest. In these settings, it was logical to refer to the area deeper than this as part of the abyssal plain. The global geomorphology classification study by Harris et al. (2014) did define a continental rise along the U.S. Atlantic continental margin, but the resolution of the data and methods for that study were different, and the results were therefore not applied to this study.

Delineation of seamounts from abyssal plain was straightforward, with clear topographic breaks between the two. The mask provides a more subjective delineation of continental slope and abyssal plain regions based on professional judgement of the approximate transition zone between the two. This was done visually based on the bathymetry grid and the approximate location of gradient reduction. Using the depth contour lines was another option as a way to distinguish between continental slope and abyssal landforms, but this was not selected because it was a poor fit for the actual feature breaks along the entire length of the margin. Based on examination of the changes in gradient along the margin, the demarcation mask between continental slope and abyssal areas was established generally between 4000-5000 m in depth along most of the margin. This demarcation was different for the southern region which has the dramatically different features of Blake Ridge and Blake Escarpment. Because of its character in relation to CMECS concepts, all of Blake Ridge was included in the abyssal marine basin floor category even though it gets shallower than 3000m for a small portion in the study area. The logical topographic break on the Blake Escarpment was at the base of the escarpment at a depth contour of approximately 5000 m.

Although depths greater than 3000 m in the ocean are commonly referred to as abyssal depths, along the Atlantic margin in many areas the actual depth where the continental slope flattens out onto an abyssal plain is substantially deeper. Alternatively, using a smoothed (generalized) gradient map of the margin was also evaluated, but was also not deemed an effective delineation approach in this case. Although the U.S. ECS Program refers to the continental slope and determines foot of the slope for juridical purposes, those delineations are a special use case unrelated to ecological processes or classification. The mask used to delineate among seamounts, continental slope, and abyssal regions for this study’s specific purpose of classifying CMECS geoforms is shown in **Figure 3.3**. This mask was created manually via expert interpretation, and was a modification of the flatness parameter mask used in BRESS software for the landforms analysis.

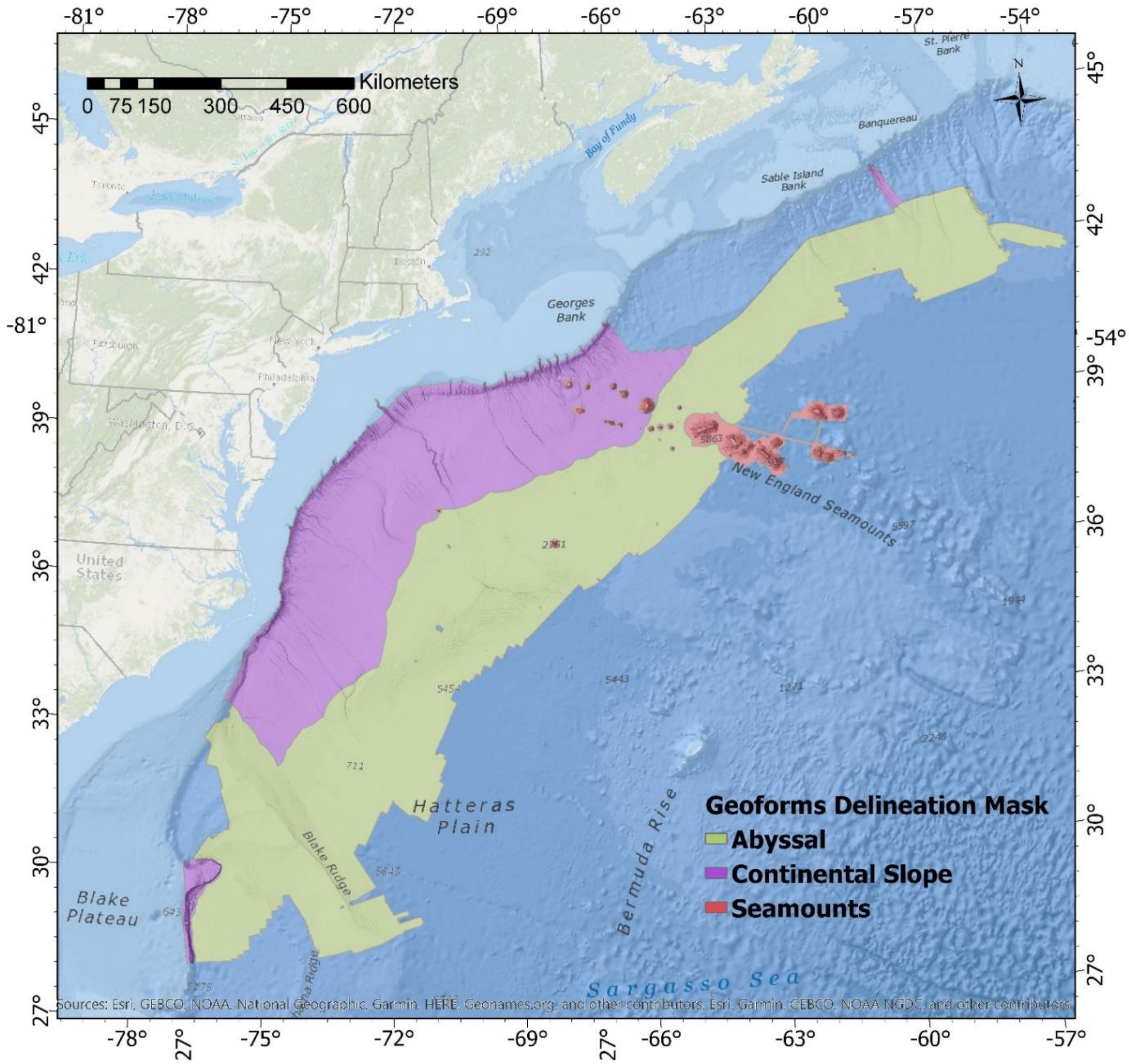

Figure 3.3. Regional mask applied to the study region in order to provide approximate CMECS classification boundaries between continental slope areas (light shading) seamounts (dark shading), and abyssal regions (medium blue shading). Bathymetry data is shown in the background for context. The key difference with the **Figure 3.2** (flatness parameter) mask is that the deep areas offshore of Canada are included with the abyssal (i.e., deep, low gradient) areas, whereas in **Figure 3.2** that area was masked differently because it had low relief features that were hard to discriminate from multibeam mapping artifacts in the bathymetry and thus needed a larger flatness parameter value.

For visualization purposes the raster grid output of landforms from BRESS was imported into QPS Fledermaus software (version 7.7.9) and draped onto the bathymetric grid. This provided for effective three-dimensional exploration of the landform interpretation directly on top of the bathymetry from which it was derived (see **Figure 3.4** in results). This method was utilized to evaluate the results of testing various search annulus and flatness parameter settings from the BRESS landforms tool, as well as for visualization of the final output prior to further geoprocessing in ArcGIS Pro.

Raster grids of the seafloor geoforms were converted in ArcGIS Pro to vector files for the creation of plots showing square kilometers within each geoform classification. These spatial files were also used to select polygons on the continental shelf to reclassify the geoform type as "continental shelf flats", and to select the flat tops of some of the seamounts (guyots) to reclassify these areas to geoform type "guyot flats." CMECS classifies guyots as a type of seamount, as the "seamount" unit is at the geoform level of the hierarchy, and "guyot" and "pinnacle seamount" are nested within this class at the geoform type level. This reclassification was done using manual selections in ArcGIS Pro software, but was limited to a small subset of the data given the small spatial extent of these geoform units relative to the size of the study region.

3.3 Results

3.3.1 Seafloor Geomorphology Maps: Landforms

The results of the landform analysis are shown in **Figure 3.4**, showing flats in purple, slopes in green, ridges in blue, and valleys in red. It is immediately notable (and expected) that the dominant landform class in the region is flats. The classification of flat doesn't mean an area lacks any slope, it is classified as such in relation to the surrounding terrain and subject to the flatness parameter defined in BRESS. Slope landforms are the second-most dominant class, and together with flats show the dominant relief features of the Atlantic margin even at the broad scale of the entire study region. Ridge and valley features provide insightful details into the structure and complexity of the continental slope canyons, abyssal bedform fields, and seamount features (see insets in **Figure 3.4**). Overall the landform results exhibit logical topographic breaks when draped over the bathymetry data, and the automated classification process from BRESS clearly works well for this purpose.

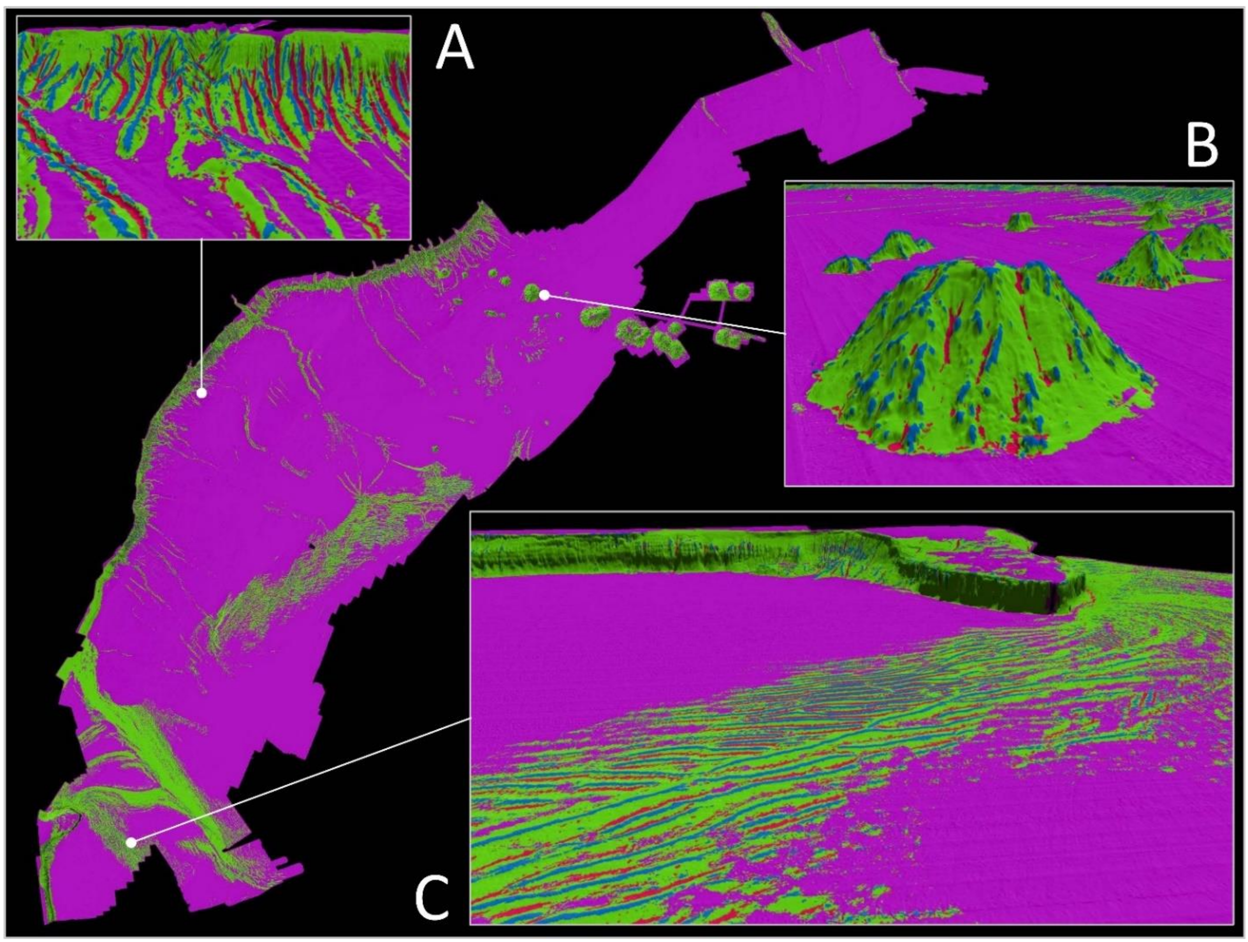

Figure 3.4. Continuous coverage landform map of the Atlantic margin study region classified into four landform types: flats (purple), slopes (green), ridges (blue), and valleys (red). Oblique

3-D inset views of landform type draped on bathymetry provided to show details. Note the clear delineation of canyon ridges, valleys, and steep slopes on the continental slope (A). Seamount features are dominated by very steep slopes with occasional ridge and valley features (B). Several large regions of the abyssal plains exhibit bedform features that follow a distinct pattern of repeating crest and trough (slope and ridge landform) combinations. Bottom right inset highlights one of these bedform fields east of the prominent Blake Spur feature (C). Figure made with QPS Fledermaus software version 7.7.9. with vertical exaggeration of 4x.

3.3.2 Seafloor Geomorphology Maps: Geoforms

CMECS geoform maps derived from the landform maps are shown in **Figures 3.5 to 3.11**. Results are shown separately for seamounts (**Figure 3.5 and Figure 3.6**), continental slope features (**Figures 3.7 and 3.8**), and abyssal features (**Figure 3.9**). For each of these regions the area of each geoform unit class, and percent contribution of each class to the whole area, were calculated. Area is report in square kilometers. The relative dominance or rarity of geoform types has ramifications for the potential habitat role of these areas, and can inform management decisions pertaining to regional marine spatial planning.

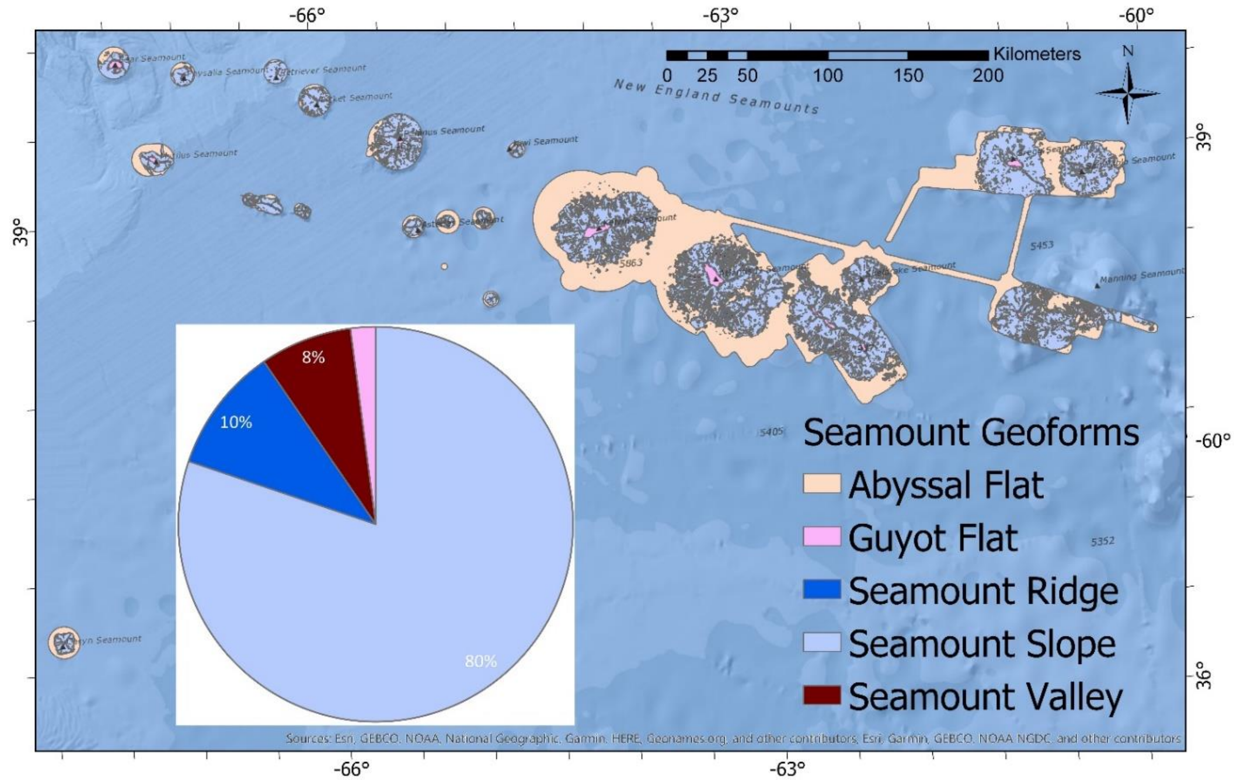

Figure 3.5. CMECS geoform classifications specific to seamounts. The tan area shown in the figure met the definition of the "abyssal flat" class and was added to that class for calculating overall study region summary statistics and for the map shown in **Figure 3.11** of all geoform classes for the whole region.

Seamount geoforms are dominated by seamount slopes (80% by area). The second most notable features are seamount ridges (10%), followed by seamount valleys (8%). The uniform steepness of the seamounts on all sides and scarcity of consistent prominent ridge features as visible from the maps is consistent with these numbers. The rarity of the guyot flat class (2%) highlights how small these features truly are by area, even though their visual interest in bathymetric maps immediately makes an impression on the interpreter. Only 9 out of the 28 seamounts within the study region have flats at their tops (guyot flats). The other 19 are pinnacle seamounts.

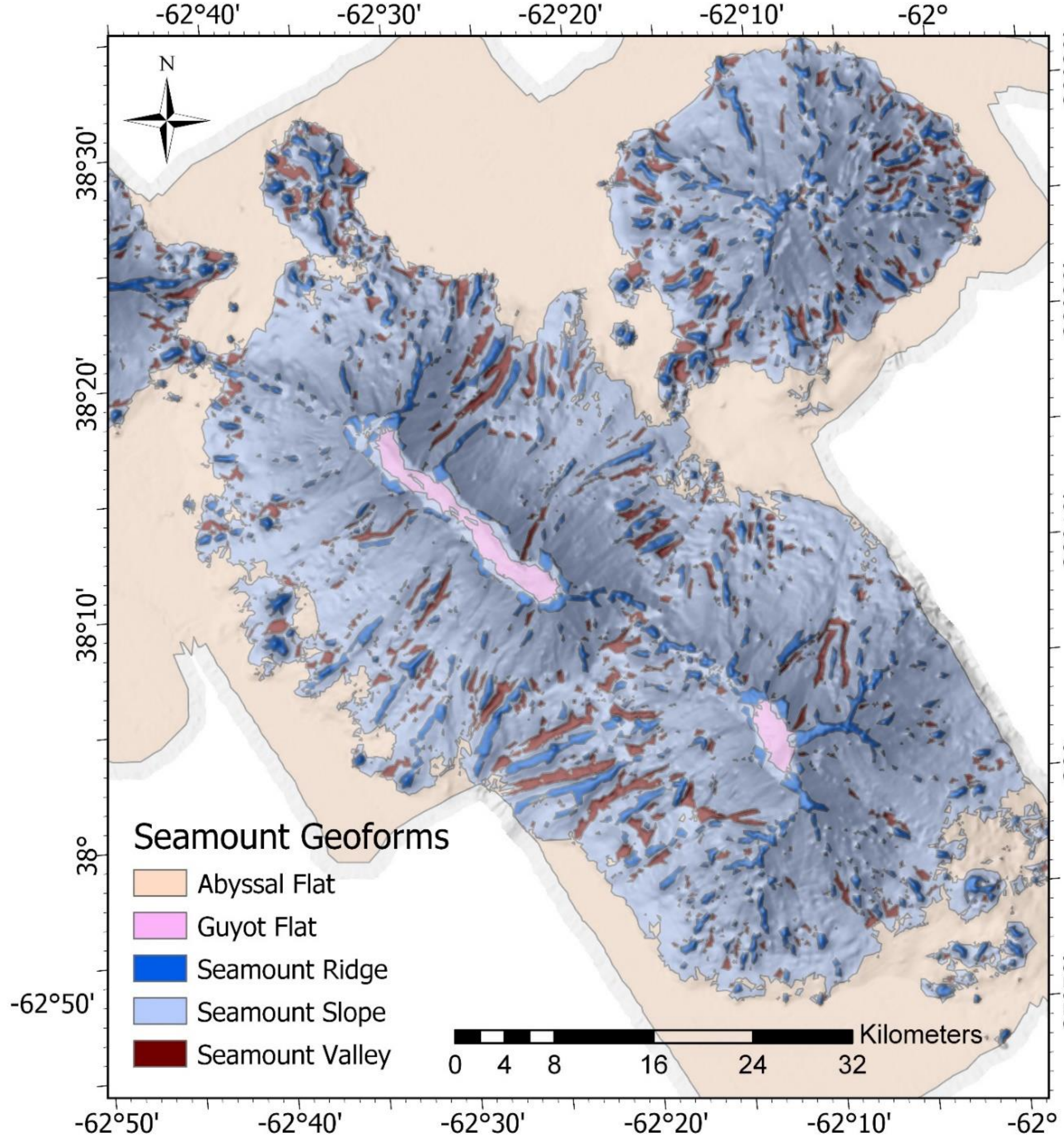

Figure 3.6. Geoforms classes of Gosnold Seamount. A hillshade layer was computed from the bathymetry and is shown with partial transparency to provide depth and context to the figure.

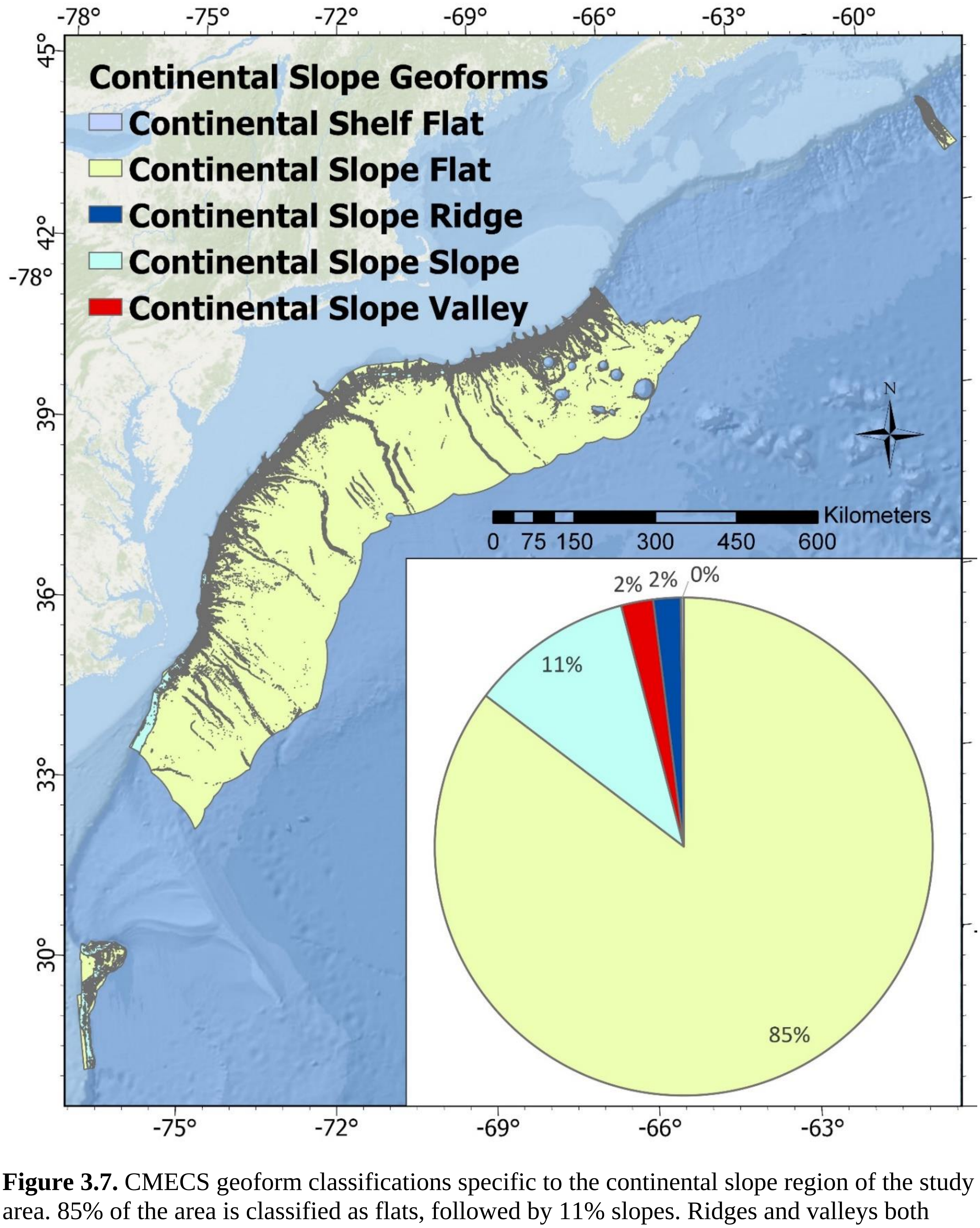

Figure 3.7. CMECS geoform classifications specific to the continental slope region of the study area. 85% of the area is classified as flats, followed by 11% slopes. Ridges and valleys both comprised 2% each. A very small portion of the mapped area in the study (0.2%) was classified as continental shelf flat (in the shallow areas above the heads of the canyons). These results highlight the fact the continental slope drops off dramatically within a relatively short distance

down the steep Atlantic canyons region of the margin (with slopes typically ranging 5-60 degrees), then exhibits a mild gradient down to abyssal depths. While the “continental slope flat” geoform type (yellow green) occurs on the continental slope, it is classified as a flat relative to the steepness of the canyons region, and due to the fact that slopes in these areas are nearly uniformly gradual and tend to range from about 0.1-1.5 degrees.

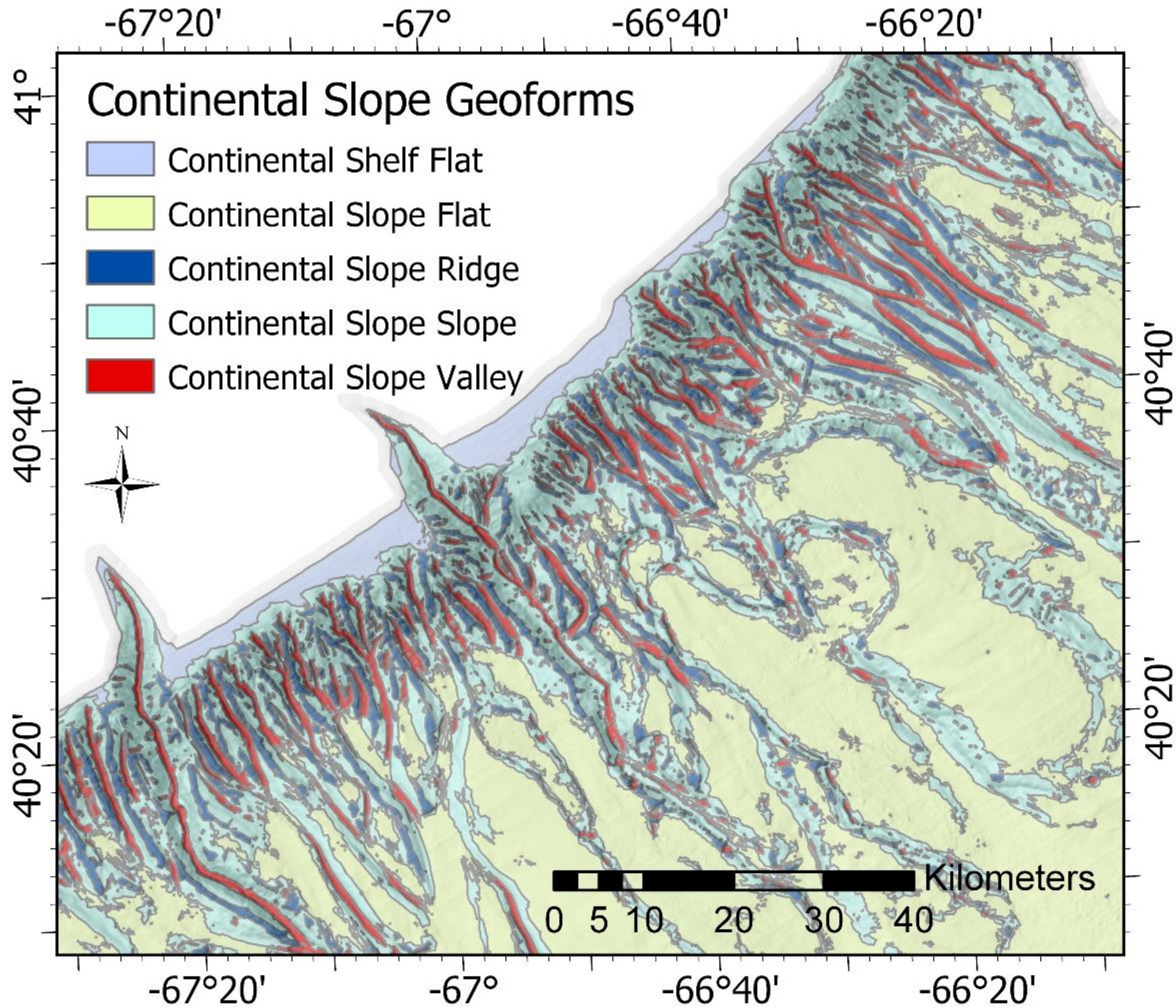

Figure 3.8. Prominent submarine canyon features on the continental slope in the Mid-Atlantic as classified by CMECS geoforms. This geoform map clearly highlights the extensive network of gullies and submarine canyons that are a signature feature of the region. A hillshade layer was computed from the bathymetry and is shown with partial transparency to provide depth and context to the figure.

In the abyssal region 84% of the area is classified as flats, 13% as slopes, 2% as ridges, and about 1% as valleys. Notable geoform characteristics of this region include the dominance of flats, the major contribution of the Blake Ridge feature to the slope class, and the importance of the bedform sediment wave formations in the U.S. Mid- and South-Atlantic regions to the slope, ridge, and valley classes. Bedform features and broad shallow submarine channels offshore of the Canadian margin do exist, but were not picked up by the methods used in this study given their smaller extent and vertical relief.

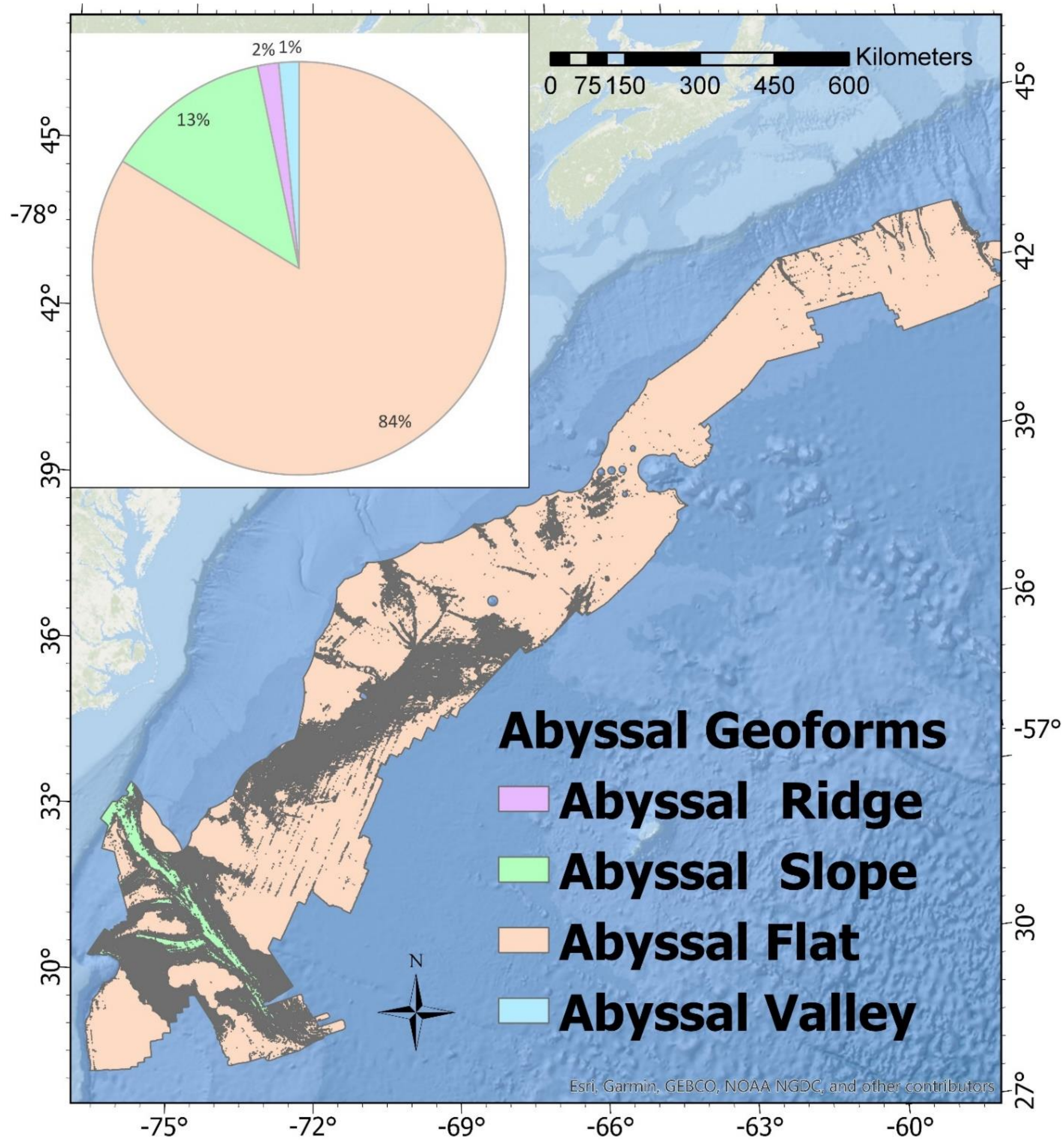

Figure 3.9. CMECS geoform classifications for the abyssal region of the Atlantic margin. Grey regions in the figure are polygons of varying classes of abyssal geoforms that cannot be distinguished at the map scale shown.

Figure 3.10 shows a complex region of the study area encompassing portions of Blake Escarpment, Blake Spur, and Blake Ridge. The figure provides mapped geoforms in both the continental shelf and abyssal portions of the study area. The bedform features in the right corner of the figure are striking, with crest-to-crest distances between about 2000-3000 meters.

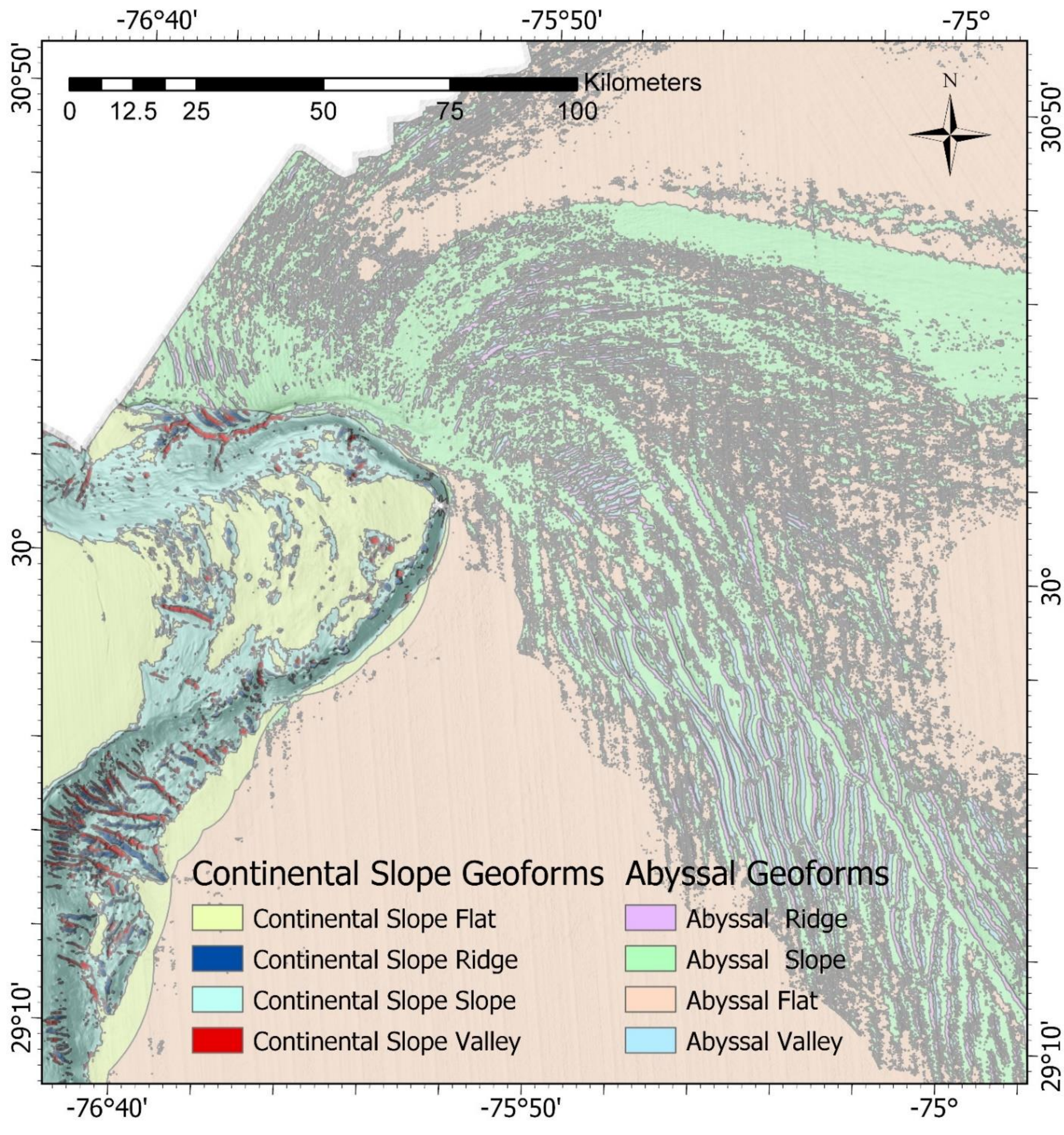

Figure 3.10. Geoform view of part of the Blake Escarpment and Blake Ridge.

Figure 3.11 illustrates the results for all geoform classes across the entire Atlantic margin study area. Abyssal flats make up more than half of the area (53%), with the continental slope flat class making up another 30% of the total area. Flats of any geoform class (including continental shelf flats and guyot flats) make up 83.06% of the study area. Slope classes make up a cumulative total of 13.26% of the study region (8.27% abyssal slopes, 3.73% continental slopes, 1.25% seamount slopes). While ridge features comprise only 1.82% of the total study area (1.03% abyssal ridges, 0.63 continental slope ridge, and 0.16% seamount ridges). The area (in square kilometers) and percentage calculations for each geoform class are shown in **Table 3.2.**

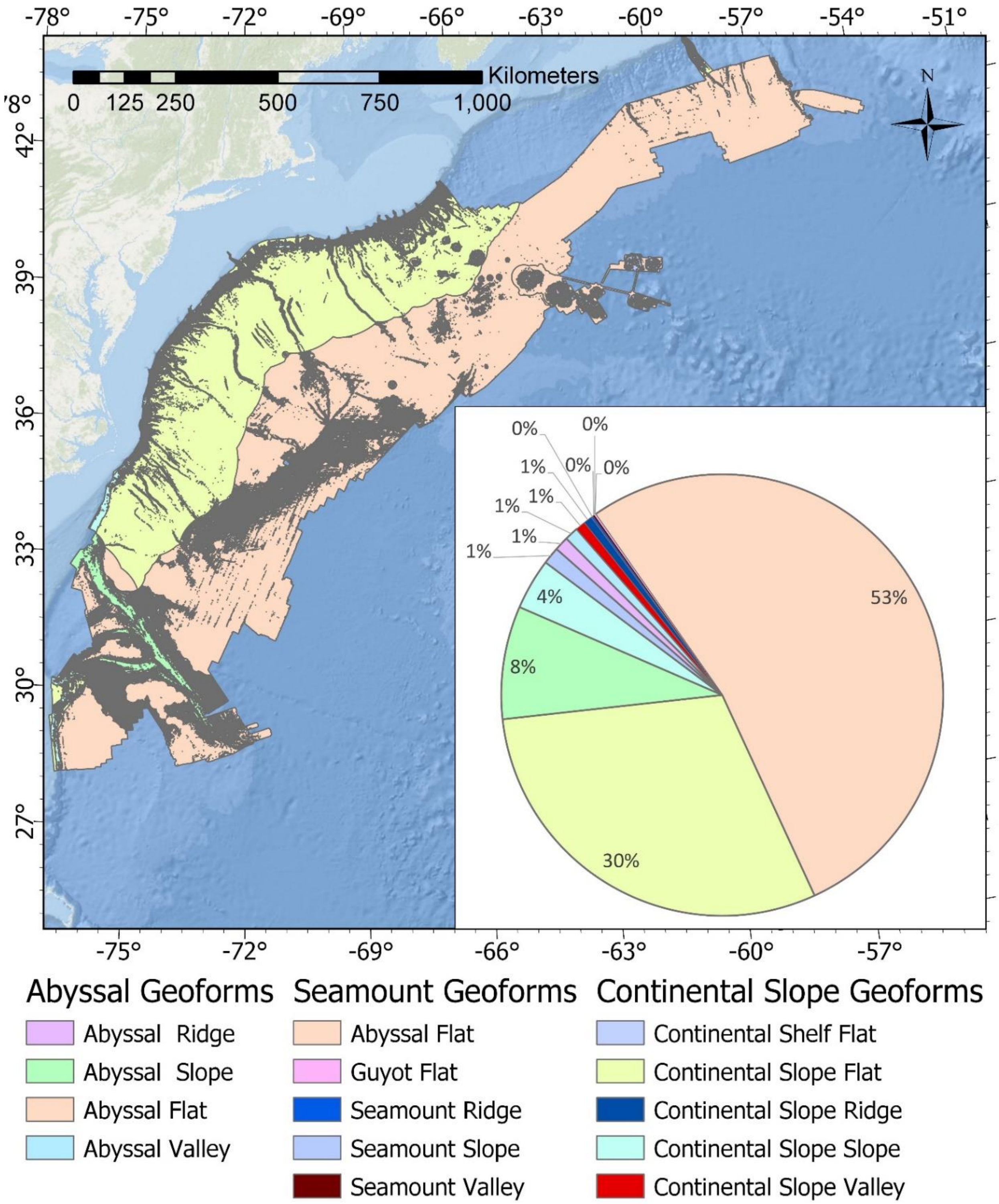

Figure 3.11. CMECS geoform classifications for the entire Atlantic margin region in the study.

Table 3.2. Geoform classes of the Atlantic margin study region by area and percentage.

Mapped Geoform Classification Unit	Area (square km)	Percent of Margin
Abyssal Flat	507,354.97	52.86
Continental Slope Flat	289,047.2	30.11
Abyssal Slope	79,427.9	8.27
Continental Slope Slope	35,851.2	3.73
Seamount Slope	11,978.5	1.25
Abyssal Ridge	9,929.6	1.03
Abyssal Valley	9,602.9	1.00
Continental Slope Valley	7,065	0.74
Continental Slope Ridge	6,047.7	0.63
Seamount Ridge	1,531.8	0.16
Seamount Valley	1,125.5	0.12
Continental Shelf Flat	606.8	0.06
Guyot Flat	306.3	0.03

3.4 Discussion

3.4.1 Advantages of the Semi-Automated Standardized Geomorphic Classification

This study tested the application of semi-automated terrain analysis methods and a standardized geomorphic classification scheme to a diverse region of the deep sea. The BRESS terrain analysis algorithm was effective at generating meaningful landform maps that could be readily translated to existing and proposed CMECS geoform units. Benefits of the tested methods include the following:

- The generation of landform results is repeatable and documented. The BRESS tool is based on a published mathematical terrain modelling approach, and is therefore not a "black box" tool. While improvements and refinements can be made to the algorithm, the methods are transparent.

- The semi-automated approach provides high speed classification of terrain over very large areas and complex terrain. The study area encompassed 959,875 km^2. The classification work presented in this paper represents several months of focused full time analytical effort (not including initial pilot studies, refinement of study analysis methods, and improvements to software interfaces). Full coverage manual interpretation of landforms and geoforms by a skilled analyst to a comparable level of detail is estimated to take 3 to 5x longer.
- The classification of landforms using the study methods involve far less subjectivity than classification methods conducted manually via expert interpretation.
- The line-of-sight analytical approach to terrain analysis employed in BRESS provides benefits in its ability to self-scale to features in the terrain as versus fixed neighborhood moving window algorithms.
- The methods are adaptable to data collected with different sensors and resolutions. The BRESS landform analysis tool can utilize bathymetry data independent of the technology used to generate the data. CMECS is also designed to be data agnostic. Both of these tools can be utilized to perform similar processing workflows that remain useful with emerging seafloor mapping technology and higher resolution maps.
- The methods are scalable to very large ocean regions, making them promising tools for interpreting data collected at regional scales and in international waters.
- Due to standardized processing methods and terminology this approach can enable integration of data sets from a variety of sources and provide outputs useable across a variety of ocean governance boundaries.

3.4.2 Limitations of the Approach

This approach is subject to limitations typical for studies employing methods to describe and map marine habitat, including the fact that all interpretation of remotely sensed information about the marine environment is constrained by issues of spatial and temporal scale and resolution of measurement data. This study was effective at classifying broad scale features discernible from a 100m resolution bathymetric grid generated from full coverage multibeam sonar data. Smaller geomorphic pattern detection is always limited by resolution and scale considerations. The BRESS tool used in this study currently requires several trial-and-error cycles to get the parameters fine-tuned to the study area. In addition, manually-generated mask spatial layers based on subjective expert interpretation were still needed to adjust the flatness parameter across the terrain, to generally delineate among continental slope, abyss, and seamount regions, and to quality control a small subset of the landform classification output. The current study is one of several other applications of the landform modeling tool aimed at improving use guidelines and best practices.

As described in the methods section, the analysis results are fairly sensitive to the selection of an appropriate flatness angle parameter. Common artifacts in multibeam mapping data result from greater uncertainty in the seafloor bottom detections of the outer beams even for fully calibrated systems with regular sound velocity measurements being taken while surveying. In several thousand meters of water depth these striping artifacts in the mapping swath can result in bathymetric grid artifacts that can partially mask seafloor features of interest. In this setting, choosing a low flatness angle in BRESS can classify low relief features like the channels shown in **Figure 3.12.** However, that is often at the expense of also classifying the striping artifacts that are also embedded into the bathymetric grid (which are not real geomorphic features). In this case, choosing a higher value for the flatness parameter ignores the classification of undesired artifacts, but also loses the ability to classify features of interest like the abyssal channels in **Figure 3.12.** This area was ultimately assigned a higher flatness parameter of 3.0 degrees in the BRESS tool in order to avoid identifying the multibeam striping artifacts as landform features.

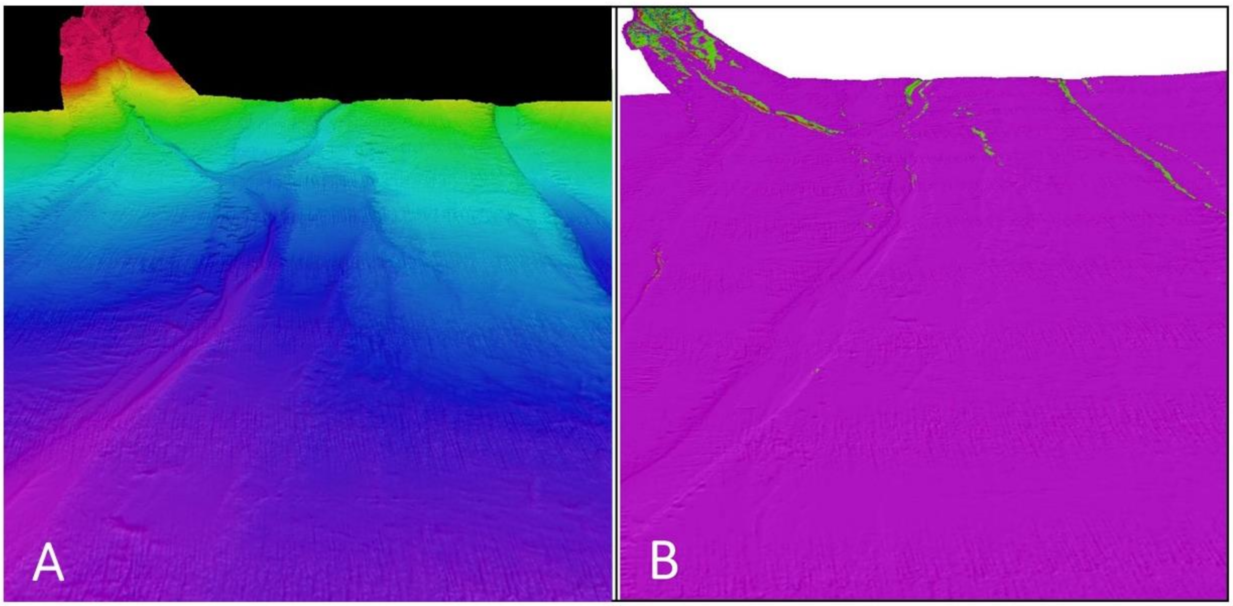

Figure 3.12. Perspective view comparison of bathymetry data (A) with the classified landform results as draped on bathymetry (B). Note the presence of channel features in the bathymetry that could not be resolved as geoforms using the landform parameters applied (they were classified as flats as represented by the purple color).

Complex combinations of landform elements that together aggregate into larger geomorphic features of interest were not identified in this study. A good example is the bedform features found in the abyssal plains of the study area. While the study effectively classified the slope, ridge, and valley combinations that comprise the components of larger geoforms such as "sediment wave field," the ability to automatically classify these aggregate geoforms is the subject of future research.

3.4.3 Potential Applications of CMECS Geomorphic Maps

CMECS geoform maps for the Atlantic margin provide insights useful for informing additional characterization of the region, and for informing current management decisions. The clear delineation of channels (i.e., the red continental slope valley features shown in **Figure 3.8**) for the Atlantic canyons makes it easy to see the low points and gain insights into the potential pathways of sediment transport out onto the abyssal basins. Their delineation from the surrounding terrain makes it easy to identify and enumerate the number of distinct canyon channels and continental shelf gullies more easily than by examining the bathymetry directly. This facilitates a better assessment of the nature and number of gully and submarine canyon features on this margin, and provides a quantitative methodical basis by which to compare these attributes to the same type of features on other continental margins. Similarly, the ability to automatically delineate significant ridge features within canyons has implications for assessing the habitat associations of organisms that may utilize these features.

The relative rarity of steep slopes (i.e., >3 degree angle from surrounding terrain) and ridges in the continental slope (11 and 2%, respectively) is striking. These areas have proven to be some of the highest likelihood places capable of supporting deep sea coral and sponge communities that often attach to steep exposed hard surfaces (Quattrini et al., 2015). The canyons area is clearly a hotspot of geodiversity, and has been recognized as a hotspot for biological diversity as well. The delineation of the canyon systems into flat, slope, ridge, and valley geoforms enables simple calculations of the relative number and area of these features within a given area of interest. This type of quantitative data on marine seascapes supports more informed marine resource management decisions, including strategic planning of marine protected area designations.

The extreme rarity of the guyot flat class (0.03 % of the total area of the study region) make them a potentially vulnerable habitat. Extractive fishing pressure (Clark, 2010), seafloor mining activities (Miller et al., 2018), and potential impacts from climate change (Levin, 2019) could impact these relatively small areas in different ways than more abundant geoforms and a precautionary approach to management is appropriate given their relative scarcity in the marine environment. Limited exploration of seamounts to date has revealed that many of these features also serve as hotspots of biological diversity and habitat for deep sea coral and sponge communities (Kennedy et al., 2019).

The ability to quickly and automatically classify features such as steep slopes and ridges, generate accurate spatial datasets of these features, and calculate the area encompassed within them, should be of great interest to marine predictive habitat modelers. While depth (bathymetry) is a common variable in habitat suitability modeling, having spatial layers of geoforms that are known to be strongly correlated with the presence of certain species or communities of biotic importance could support more powerful and accurate predictive models (e.g., Savini et al., 2014).

3.5 Conclusions

Our results provide a characterization of the marine landscape that serves as an inventory of the cumulative area and abundance of geoforms and the spatial relationships among them. The derived maps and associated databases can be used for a broad range of spatial analyses defined by other end users to inform management decisions. Geoform summary statistics were calculated over the study region to quantify the area of each geoform type. These analyses represent a first step in identifying regions of consistent morphology within which the consistency of the backscatter can then be determined (Masetti et al., 2018).

The approach developed through this work provides a model of how to consistently classify ecological marine units using CMECS as an organizing framework across large continental margin regions nationally or globally. Given that many nations have already invested heavily in gathering bathymetric data for these areas, this approach can be adopted to obtain a standardized interpretation to inform baseline marine habitat characterization in support of ecosystem-based management.

Acknowledgements

The authors wish to acknowledge the contribution of the following collaborators to this study. Dr. Larry Ward for discussions and refinement of ideas on refining the BRESS software tool and converting landform classes to geoforms. Dr. James V. Gardner for conceptualization of value-added uses for ECS datasets and leadership completing bathymetric surveys of the study area. Mark Finkbeiner for expert advice and guidance on the application of CMECS and development of this dynamic content standard. The captains and crews of all of the oceanographic vessels involved in gathering the bathymetric data for the study.

Chapter 4

Standardized Geomorphic Characterization of the Extensive Cold-Water Coral Mound Province of the Blake Plateau, USA

Abstract

Extensive cold-water coral (CWC) mound ecosystems around the planet are being revealed for the first time as ocean mapping and exploration efforts of the deep sea increase. A coordinated multi-year exploration campaign on the Blake Plateau offshore of the southeastern U.S. has mapped what appears to be the most expansive CWC mound province thus far discovered. Nearly continuous CWC mound features span an area up to 472 km long and 88 km wide, with a core area of high density mounds up to 248 km long by 35 km wide. This study synthesized bathymetric data from twenty multibeam sonar mapping surveys and generated a standardized geomorphic classification of the region in order to delineate and quantify CWC mound habitats and compare mound morphologies among subregions of the coral province. Based on the multibeam bathymetry, a total of 59,760 individual peak features were delineated, providing the first estimate of the overall number of potential CWC mounds mapped in the region to date. Five geomorphic landform classes were mapped and quantified: peaks (342 km^2), valleys (2,883 km^2), ridges (2,952 km^2), slopes (15,227 km^2), and flats (49,003 km^2). The complex geomorphology of eight subregions was described qualitatively with geomorphic "fingerprints" and quantitatively by measurements of mound density and vertical relief. The

median mound relief for the entire study region was 14 m, with individual mound features ranging 3-178 meters above the adjacent seafloor. Mound peak densities reached up to 4.79 mounds/km^2. Ground-truth for the bathymetric analysis was provided by direct substrate observations from 23 submersible dive videos that revealed coral rubble to be the dominant substrate component within the peak, ridge, and slope landforms explored, thereby validating the interpretation of these bathymetric features as CWC mounds even on features with as little as 10 meters of average vertical relief above the surrounding seafloor. Results indicate that the Blake Plateau supports a globally exceptional CWC mound province of heretofore unprecedented scale and diverse morphological complexity.

4.1 Introduction

4.1.1 Background on Cold-water Coral Mounds

Deep water cold-water corals (CWCs) grow in the absence of sunlight in deeper water of the world's oceans and filter feed on suspended particles in the water column. CWCs have been documented to inhabit many parts of the deep ocean once thought to support minimal benthic fauna. The global distribution of CWC species is poorly understood given that the majority of the global deep ocean is yet to be mapped or explored. However, CWCs appear to be mainly restricted to oceanic waters with within a temperature range of 4-12°C (Roberts et al., 2006). Many CWC species are affiliated with hard substrates and geologic features that offer steeper slopes, exposed bedrock, or coarse drop-stone materials for attachment to the seafloor (Quattrini et al., 2015; Wheeler et al., 2007). Dense aggregations of CWCs are also associated with regions of the ocean that sustain high primary productivity in overlying waters and reliable currents for food delivery to the stationary corals (Genin et al., 1986).

Some CWC species can build calcium carbonate based reef structures referred to by a variety of terms including coral banks, lithoherms, and bioherms (Messing et al., 1990; Reed, 2002; Stetson et al., 1962). A bioherm is a type of mound composed of unconsolidated sediment and coral skeletal material capped with coral thickets (Reed, 2002), whereas a lithoherm is a mound composed of high-relief lithified carbonate that may be covered with live coral (Neumann et al.,1977). CWC reefs have been documented off the coasts of at least 41 countries thus far (Freiwald et al., 2004).

Cold-water scleractinian ("stony coral") species such as *Lophelia, Enallopsammia, Madrepora, Oculina,* and *Solenosmilia* grow dense calcareous skeletal frameworks that can build extensive biogenic coral mounds ranging in vertical relief from tens to hundreds of meters (Reed et al., 2006). These mound features have been discovered around the world clustering in "provinces" where food supply and strong currents support coral growth (Roberts et al., 2009). These CWC reefs provide complex structure and hard substrate that provide habitat for many associated corals, sponges, invertebrates, and fishes (Henry and Roberts, 2016). Reef forming CWC species therefore serve as autogenic "ecosystem engineers" (also referred to as foundation species) by substantially modifying the surrounding environment and creating habitat niches for many other species (Jones et al., 1994). There is also evidence that the presence of high-relief CWC mounds can affect the overlying physical oceanography. For example, CWC mounds at 600 m depth on Rockall Bank in the NE Atlantic have been shown to induce tidally-driven downwelling of organic material, providing an important carbon pump from surface waters to the deep sea (Soetaert et al., 2016).

CWC habitats are slow-growing, long-lived, and fragile, making them particularly vulnerable to physical damage by seafloor bottom contact human activities. Threats include trawling (Fosså et al., 2002), hydrocarbon and mineral exploration and production, and cable and pipeline placements (Friewald et al., 2004). The ecological importance and vulnerability of CWC reefs has resulted in increased national and international efforts to map, characterize, and protect them (Parker et al., 2009).

Multibeam sonar systems have enabled ocean scientists to map complex CWC mound and reef habitats remotely from surface ship hull-mounted sonars, with resolution directly related to the depth of the seafloor and the angular resolution of the particular multibeam system. Multibeam and sidescan sonar systems mounted on remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) can get close to the seafloor and thereby obtain much higher resolution maps of CWC mounds - typically centimeters to tens of meters resolution depending on the height above seafloor (Grasmueck et al., 2006; Kilgour et al., 2014). These systems provide higher resolution but smaller areas of coverage than ship-mounted multibeam sonars. Fine-scale ground-truth data on seafloor substrate character and biological communities at CWC sites is made possible through the use of towed or dropped camera systems, and via video data collected by AUVs, ROVs, and human occupied vehicles (HOVs) that can capture views of these habitats within meters of the seafloor.

Aggregations of CWC mounds are regularly referred to in the scientific literature as "provinces" (e.g., Angeletti et al., 2020; Hebbeln et al., 2014, Taviani et al., 2017; Wienberg et al., 2018). While there is no clear standard that defines a province, by convention they describe CWC mound complexes often spanning tens of square kilometers. The delineation of CWC provinces is pragmatically useful for management and conservation purposes such as designation of seafloor areas where bottom-disturbing activities are prohibited (Angeletti et al., 2020).

4.1.2 Cold-Water Coral Mound Province of the Blake Plateau

The region offshore of the Southeast U.S. contains the most extensive *Lophelia* and *Oculina* CWC ecosystems documented within U.S. waters (Hain and Corcoran, 2004; Partyka et al., 2007; Reed et al., 2013; Ross and Nizinski, 2007; Stetson et al., 1962). *Lophelia pertusa* is the most common reef building CWC documented in the North Atlantic and has been found in depths ranging from 39-3,383 meters (Friewald et al., 2004; Zibrowius, 1980). Studies in the Gulf of Mexico on artificial structures calculated minimum *Lophelia* growth rates of 3.2 to 32.3 mm/yr (Larcom et al., 2014). CWC mounds within the Straits of Florida have displayed growth throughout changes in geologic climate cycles over the last 600,000 years, including the last glacial maximum (Galvez, 2020). Given the slow growth rates of *Lophelia*, and that dead coral samples from mound features on the Blake Plateau have thus far been dated between 5,000 to 44,000 years old (Ayers and Pilkey, 1981), the size and nature of the mounds features in the Blake Plateau indicate that they must be many thousands of years old and would be very slow to recover from physical damage from human activities.

In response to improved information on the nature and distribution of CWC resources on the Blake Plateau, the South Atlantic Fishery Management Council (SAFMC) designated the Stetson/Miami Terrace Deep Water Coral Habitat Area of Particular Concern (HAPC) in 2010 to protect the seafloor in this area. The designation prohibits the use of bottom-contact fishing gear (bottom longline, bottom and mid-water trawl, dredge, pot, and trap), anchoring by fishing vessels, and possession of deep water coral. (SAFMC, 2020).

In 2016, the National Oceanic and Atmospheric Administration's Deep-Sea Coral Research and Technology Program initiated the Southeast Deep Coral Initiative - a focused four-year research effort to dramatically increase exploration and understanding of deep-sea coral habitats in the Southeast region of the U.S. (Wagner et al., 2017). The science plan for this initiative informed much of the exploration work and data partially synthesized and presented in this study. A separate but related key research initiative in the Southeast U.S. region was launched in 2017 called Deep-Sea Exploration to Advance Research on Corals/Canyons/Cold seeps (DEEP SEARCH) with funding from the National Oceanographic Partnership Program (Cordes, 2020). New mapping data and submersible video data from DEEP SEARCH was utilized for this paper for pertinent regions of the Blake Plateau.

4.1.3 Study Objectives and Importance

Strategic ocean exploration efforts led by NOAA's Office of Ocean Exploration and Research (OER) and the DEEP SEARCH project have provided breakthrough insights into the nature and extent of the cold-water coral ecosystems of the Blake Plateau off the southeastern United States. This study has used data collected by OER and DEEP SEARCH and other efforts to compile mapping data and video annotations interpreted from submersible (HOV and ROV) video footage to:

1. Determine the known extent of CWC mound features,
2. Generate an objective standardized geomorphic characterization of the region,
3. Examine the relationship between mound landforms and seafloor substrates, and

4. Test the application of the Coastal and Marine Ecological Classification Standard (CMECS) to substrates and geomorphic features in the study area (FGDC, 2012).

Characterization of the Blake Plateau CWC mound province extent and geomorphic diversity is of direct relevance to marine resource managers charged with implementing ecosystem-based management approaches and protecting vulnerable seafloor habitats from harmful human impacts. The results of this study also provides essential information to enable comparisons with other CWC mound provinces in order to understand the global characteristics of this ecologically critical marine habitat.

4.2 Materials and Methods

4.2.1 Study Area

The study area is located on the Blake Plateau 60-120 km offshore of the southeast U.S. coastline beginning roughly southeast of Miami, Florida (~25° N) in the south and ending southeast of Charleston, South Carolina (~32.4° N) in the north. Blake Plateau is a broad, relatively flat region of the upper continental slope of the U.S. Atlantic margin ranging from about 500-1000 m water depth. The 150-300 km wide plateau is located between the shallow continental shelf (< 200 m depth) and the Blake Escarpment continental slope that steeply drops to abyssal plains at 5000 m. This study focused on the western region of the Blake Plateau that is directly influenced by the main axis of the warm Florida Current / Gulf Stream current as it moves northward out of the Straits of Florida. The current extends to the seafloor in this area with a mean transport of 32 Sverdrup (Sv, one million cubic meters per second) at 27°N (±2-3 Sv for seasonal and interannual variability), which is equivalent to about two thousand times the annual average transport of the Mississippi River into the Gulf of Mexico (Baringer and Larsen, 2001; Richardson, 2001). Gulf Stream transport varies seasonally, with surface water transport peaking in the fall and reaching a minimum in the spring but deep water transport showing the opposite seasonal peak fluctuations and with a larger magnitude (Hogg and Johns, 1995).

The study area encompasses subregions of the Blake Plateau referred to by other researchers under a variety of names, including Stetson Reefs (Reed et al., 2002), Stetson Banks (Ross and Nizinski, 2007), Savannah Banks (Ross, 2006), Hoyt Hills, Richardson Hills, Richardson Reef, and portions of the Miami Terrace and Charleston Bump.

The primary data sources utilized for the study were based on twelve expeditions led by NOAA's Office of Ocean Exploration and Research on NOAA Ship *Okeanos Explorer,* as well as two cruises led by the Deep-Sea Exploration to Advance Research on Corals/Canyons/Cold seeps (DEEP SEARCH) project on NOAA Ship *Ronald H. Brown* and R/V *Atlantis*. Bathymetric data, as well as submersible dive video data, were utilized from all of these cruises to inform this study. Bathymetric data processing is described in section 4.2.2, while utilization of dive video data is described in section 4.2.4.

4.2.2 Bathymetric Synthesis

Data from twenty separate multibeam sonar mapping surveys were synthesized into a seamless bathymetric map with 35 m grid resolution. All data used as input to the grid are publicly available via the NOAA National Centers for Environmental Information multibeam archives (NCEI, 2004). Data incorporated into the grid are from the following cruises: EX1106, EX1202L1, EX1203, EX1403, EX1804, EX1805, EX1806, EX1812, EX1903L1, EX1903L2, EX1906, EX1907, RB1903, AT41, H11071, H11680, LCE2010, RB1008, SAB2006, and NF0702. Survey lines selected for this study were generally limited to areas shallower than the

1000 m contour line on the continental slope. The focus of this paper was on biogenic CWC mounds on the Blake Plateau, so areas deeper than this were excluded. Exploration work completed thus far along the adjacent deeper continental slope has revealed coral habitats associated with hard-bottom ledge or scarp features, but not CWC mounds.

Some publicly available multibeam data on the Blake Plateau were intentionally excluded from the bathymetric synthesis. Multibeam sonar lines from any input survey with poor quality (typically resulting from rough weather conditions) were not used. Some large multibeam survey areas in the eastern region of the Blake Plateau were excluded from the synthesis grid because they lacked visible CWC mound features. Because the focus of this study was on characterizing the geomorphology of CWC mounds in the region, inclusion of these areas would not have provided any additional information to the purpose of the study. It must be noted that there are still large gaps in coverage remaining on the Blake Plateau.

Multibeam sonar backscatter intensity mosaics were produced for most of the study areas covered by data from NOAA Ship *Okeanos Explorer* surveys. Backscatter mosaics were compared with substrate annotations from submersible dives and landform types to examine if any clear correlations were evident, but ultimately this data type was excluded from the study due to challenges in scale differences between the datasets and the need to constrain the scope of the study.

Data from each survey were quality checked and rigorously cleaned of noise and sound speed error artifacts using manual and automated editing tools within QPS Qimera software version 2.2.3. Most of the data were collected by a Kongsberg EM 302 multibeam sonar on the

Okeanos Explorer with a 0.5° x 1° transmit/receive beam width array that supported consistent quality 25 m resolution grids of the study region. Cleaned data from all sources were gridded to 25 to 30 m resolution depending on the source data quality. These individual survey grids were then exported in xyz (longitude, latitude, depth) format, reimported into a master synthesis Qimera project, and then incorporated into a seamless 35 m resolution dynamic surface. Gridding surfaces were created using Qimera’s weighted moving average algorithm with a 3x3 cell moving window. Some minor artifacts were present in the far northern portion of the synthesis grid in areas where different surveys overlapped. This region of the Blake Plateau has extremely dynamic sound speed fluctuations in the water column due to the Gulf Stream and associated eddies, but most artifacts resulting from sound speed error were resolved through editing of outer beams of the sonar swaths in the Qimera software. This intensive quality control editing of the synthesis bathymetric grid was completed in order to produce the best possible seamless map of the region so as to minimize artifacts that would affect the results of geomorphic classification in the next step of the study (section 4.2.3). The bathymetry grid and all other spatial datasets used in the study were projected to spatial reference WGS 84 / UTM zone17N (EPSG:32617). Depths in the final bathymetry synthesis grid range from 16-2700 m, with the majority of the region in the 400-800 m range and a mean depth of 740 m. The mapped area of the study region is 70,407 km^2, equivalent to about half the land area of Florida. The final 35 m resolution bathymetry grid was imported into ArcGIS Pro version 2.6.0. for further analysis.

The seamless bathymetry grid (**Figure 4.1**) was used to delineate the extent of nearly continuous CWC mound and scarp areas in the south and west portion of the study region that encompasses the largest area and densest mound features. Since there is not an agreed upon standard for what defined a CWC mound "province," two different regions were delineated to approximate a maximum and minimum extent in order to enable comparison with the areal coverage of other CWC mound provinces globally. Determining "nearly continuous" in terms of CWC mounds is a subjective process since many mound features in proximity to each other do not directly touch. For this reason, two different polygons were manually drawn in Arc using different criteria. The maximum extent polygon (white polygon **Figure 4.1**) was drawn liberally to include any areas of adjacent scarp and CWC mound features with the outer boundary being digitized where all features ceased and only flat seafloor was evident in the multibeam grid. This maximum extent polygon therefore includes some areas of large flats that are surrounded by mound and scarp features, areas with very small mound features (down to 10 m vertical relief), and some areas of low mound densities.

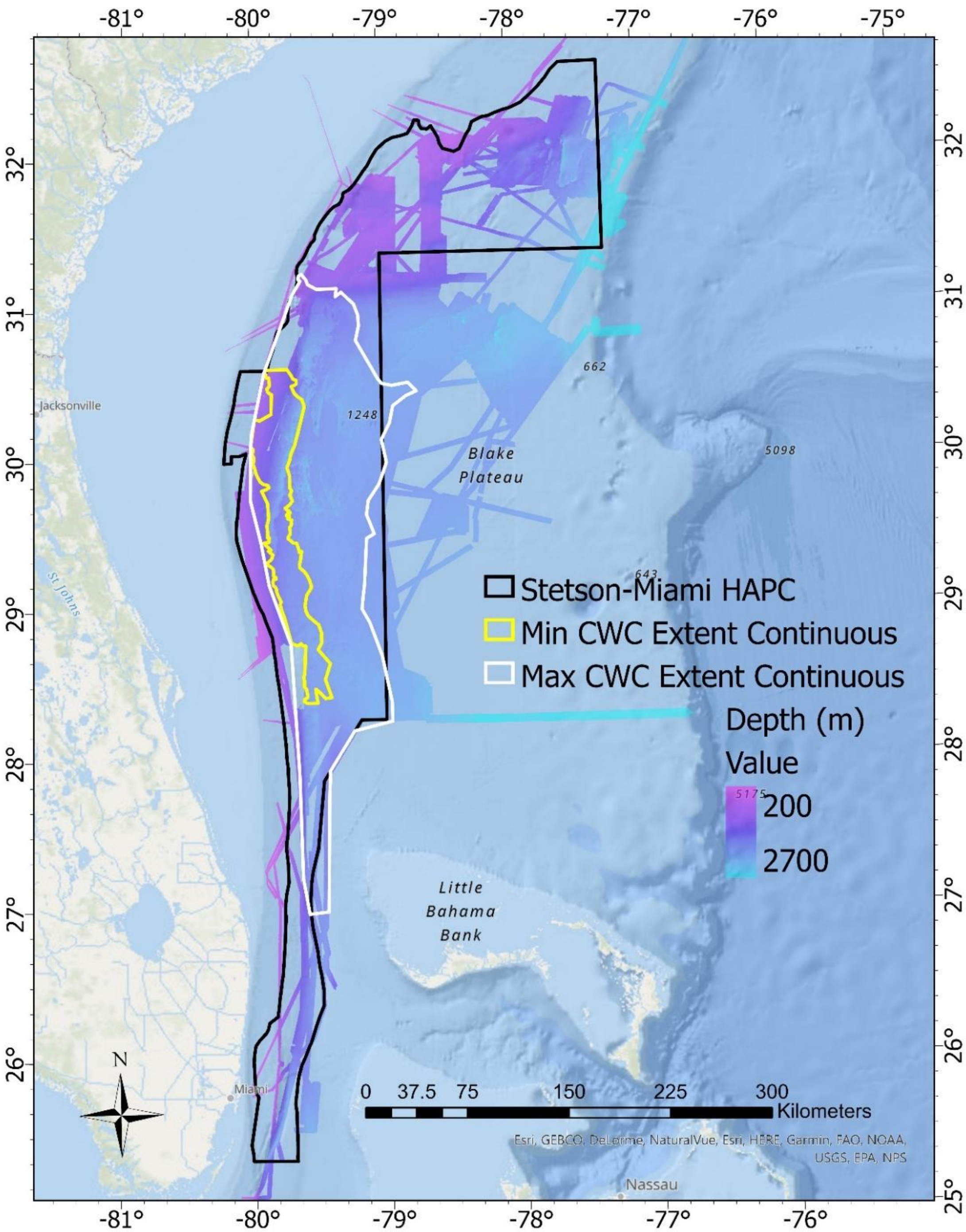

Figure 4.1. Bathymetric terrain model synthesis grid of the Blake Plateau CWC mound study region from 20 different multibeam sonar surveys. The white polygon represents the maximum extent of nearly continuous CWC mound features, the yellow polygon represents the minimum extent core area of continuous CWC features. The black polygon shows the existing boundaries of the Stetson-Miami Deepwater Coral Habitat Area of Particular Concern.

A second smaller polygon was digitized to only include the core area of very dense mound aggregations within the maximum extent polygon. The purpose of this polygon was to define an extent of nearly continuous CWC mound features that is very conservative and essentially limited to places where the base of one mound slope touches an adjacent mound (yellow polygon **Figure 4.1**). There is a fairly distinct landscape morphology change moving from west to east within this area: from densely packed mounds to more widely spaced mounds in the southern half, and a shift to scarp and ridge features in the northern half. The approximate transition between these different east/west morphologies was used to define the eastern edge of the core area polygon. The core area of dense mounds is referred to in this study as the "Million Mounds" subregion based on a nickname it was given by scientists during recent mapping and ROV expeditions. **Figure 4.3** shows a relatively fine scale view of the Million Mounds area showing the minimum extent polygon of continuous mound features (yellow line), and the maximum extent polygon (white line) to highlight the different criteria used in digitizing these proposed province extent boundaries.

4.2.3 Geomorphic Analysis of Study Area

An objective geomorphic landform classification of the region was derived from the bathymetry using the Bathymetry- and Reflectivity-based Estimator for Seafloor Segmentation (BRESS) method developed by Masetti et al. (2018). The geomorphic classification approach taken in this study builds on methods applied to the Atlantic continental slope, abyssal plains, and seamounts along the U.S. Atlantic margin (Sowers et al., 2019, 2020), and the reader is referred to these publications for discussion of selecting and testing suitable modeling parameters for a given study area. Details about the theoretical framework of this approach can be found in

Jasiewicz and Stepinski (2013). BRESS is available as a free stand-alone application at https://www.hydroffice.org/bress/main (Hydroffice, 2019). Version 2.2.2 was utilized for this study.

The BRESS analytical approach identifies terrain features that can be classified into easily recognizable landform types such as valleys, slopes, ridges, and flats. These landform archetypes are referred to as “bathymorphons” and represent the relative landscape relationships between a single node in the bathymetric grid and the surrounding grid nodes as assessed in eight directions around the node. This relative position is determined via a line-of-sight method looking out in each direction by a user-defined search annulus specified by an inner and outer search radius. The algorithm generates aggregations of the same bathymorphon type and utilizes a look-up classification table to translate these patterns into landform types.

The classification types for this study were selected to delineate the most essential components of CWC mound and geologic scarp features that comprise the notable geomorphic features in the study region, while striving for simplicity. A driving determinant of the selection of landform classes was the study aim to be able to effectively delineate and quantify CWC mound peak features from the rest of the terrain. This objective was critical as assessing the number, density, and vertical relief of CWC mound features across the extent of the region and comparing among subregions was deemed an essential way to characterize the CWC province. The following landform types were selected to meet the study goals while enabling the classification of a continuous geomorphic map of the region: flat, slope, valley, ridge, and peak.

The multibeam synthesis grid described in section 4.2.2 was exported from QPS Fledermaus software version 7.8.7 in ASCII grid format projected to spatial reference WGS 84 / UTM zone17N (EPSG:32617) and used as the input dataset for the BRESS version 2.2.2 software analysis. Inner and outer search radii and the flatness parameter in BRESS were iteratively tested until an inner search radius of 1 grid node (35 m distance), an outer search radius of 6 grid nodes (210 m), and a flatness parameter of 1.5 degrees was found to yield the best results (i.e. the most comparable results to what would be manually classified by a skilled analyst working on the same dataset in order to delineate geomorphic features of interest – particularly CWC mound peak features). Given these parameters, the smallest landform unit classified by the geomorphic analysis is 35 m, and any mound peak features smaller than this would not be classified as such. Results of model landform classification output were draped onto 3D bathymetry using QPS Fledermaus software to confirm that delineations between landform classes were logical and comparable to feature breaks that could be made manually by a skilled analyst.

A raster grid of landform classes was exported from BRESS in ASCII grid format and imported into ArcGIS Pro v2.6.0 for further analysis. The “Int” geoprocessing tool was used run on the raster in order to designate each cell of the grid as an integer value instead of a floating point value. This was done to ensure correct symbology of the layer. The “Raster to Polygon” geoprocessing tool was then used to convert the raster grid to a polygon feature class, with individual polygons for all flat, peak, slope, ridge, and valley landforms recorded in an attribute table. The “simplify polygon” option was used. A new field was added to the attribute table and the “calculate field” tool was used to calculate the area of each polygon in square meters using a geodesic area calculation. This method avoids area calculations with lower accuracy when using a projected coordinate system that is not equal-area. The "summary statistics" tool was then used to calculate cumulative areas for each landform class for the entire study region.

4.2.4 Geomorphic Analysis of Subregions and Mound Relief

Upon inspection of the geomorphology landforms layer of the Blake Plateau study area it was readily apparent that there was a striking diversity of geomorphic patterns in the terrain that varied dramatically by subregion. The methods described in this section were used to characterize these geomorphic differences both qualitatively and quantitatively. To quantify differences of CWC mound characteristics across the Blake Plateau, additional spatial analysis was done using ArcGIS Pro v2.6.0.

The first step in the subregional characterization of CWC mound features was to subjectively select and delineate the subregions. Eight subregions of the overall study area were selected based on the following rationale:

- Two were selected as examples of large mounds formed along the top of steep geologic scarp features of the terrain ("Jellyfish Mounds" and "Richardson Mounds");
- Four subregions were selected based on their unique spatial pattern of mound features not observed elsewhere in the region ("Streamlined Mounds," "Ripple Mounds," "Mini Mounds," and "Sparse Mounds");
- One region was selected as a large newly mapped CWC mound area outside the existing coral Habitat Area of Particular Concern protection boundary ("Pinnacle Mounds"). Sparse Mounds also met this criterion.

- One was selected for its exceptionally high mound densities over a large continuous spatial extent (“Million Mounds”). This area forms the core of the largest continuous extent of coral described in the paper (white polygon in **Figure 4.1**).

Bounding polygons for each of these eight areas were then hand-digitized in Arc using the bathymetry and landform layers to discriminate between areas of CWC mounds and surrounding flat terrain. To highlight the qualitative differences in landform patterns, plan view figures were created for the eight subregions to visually display the diverse geomorphic “fingerprints” (i.e. pattern arrangement) of the landforms comprising each area. Figures of landform patterns were draped on the bathymetry in QPS Fledermaus to enhance visualization.

Within each of the eight subregions the following metrics were calculated in ArcGIS Pro v2.6.0: number of mound peaks, peak density (number of peaks per km^2), area of peak landforms, areas of ridge landforms, and mound peak minimum and maximum depths. To calculate these metrics, the vector layer of landform polygons was clipped to the subregion extent, the summary statistics tool was used to summarize the number of peak features and generate areas for peak and ridge landform classes. All areas were calculated using a geodesic formula to generate accurate area values undistorted by the map projection. To calculate the minimum and maximum depth of mound peak features the “extract by mask” geoprocessing tool was used to mask the bathymetry layer with a vector layer of only peak landform features for each subregion. Minimum and maximum depth values were then noted for the resulting output raster.

The vertical relief of a CWC mound above surrounding terrain is a defining characteristic of mound morphology. Relief above surrounding seafloor will also determine the hydrodynamic conditions affecting the slopes, ridges, and peaks of the mound thereby directly influencing currents and food delivery to CWCs and associated biota. Therefore, additional metrics designed to quantify the vertical relief of mound features from surrounding terrain were deemed important, and six metrics were calculated pertaining specifically to mound relief within each subregion: mound relief range, minimum, maximum, mean, median, and standard deviation. In order to generate statistics of mound relief a methodology was needed to calculate the approximate relief of any given mound feature from the surrounding terrain at the base of the mound.

The BRESS software can generate an optional statistical spatial layer output called “maximum height delta” that calculates the maximum change in height measured from any grid node to its surrounding visual neighborhood in eight line-of-sight directions. This calculation is limited to surrounding grid cells that fall within the user-specified inner and outer search radii parameters. The BRESS model run used to delineate landforms had inner and outer search radii set to 35 m and 210 m, respectively. While these radii parameters were optimized to effectively delineate CWC mound peak features, the outer radius of 210 m was not deemed adequate for calculating maximum height delta values because it truncated possible vertical relief values and resulted in underestimating the relief of mound features when compared with actual direct measurements of relief from the bathymetry of select test mounds. By direct measurement of the largest mounds in the bathymetry grid, a distance of 420 m was deemed able to capture the maximum vertical relief change from the top of any mound feature to the surrounding seafloor flats. Based on this, an additional model run of BRESS was completed on the bathymetric grid using an adjusted outer search radius value of 12 nodes (420 m) and the maximum height delta spatial output layer was saved and imported into ArcGIS Pro v2.6.0.

Mound relief values were calculated by using the subregional boundary polygons to clip the maximum height delta spatial layer in ArcGIS Pro v2.6.0. The result was a feature layer for each subregion that had individual polygons of only areas classified as peak landforms and attributed with values of maximum delta heights. The summary statistics geoprocessing tool was then run on this feature layer querying for statistics on the sum of polygon areas, range, minimum, maximum, mean, median, and standard deviation. These values were then aggregated into a table of statistics from all subregions to enable comparisons.

4.2.5 Substrate Classification and Comparison with Landforms

An objective of this study is to examine how substrate classes differ among the geomorphic landform types classified based on remotely-sensed multibeam sonar mapping data. In order to address this objective, reliable observations of seafloor substrate character were needed with accurate positioning and good spatial coverage over the CWC mound features of primary study interest. Substrate “groundtruth” data for this purpose needed to be actual seafloor observation data from cameras or videos because the intent was to classify the primary dominant substrate type based on visual percent cover.

Video data recorded from 23 submersible dives were used to assess the substrate character within classified landforms: fifteen dives were completed using the dual-body *Deep Discover*/*Seirios* ROVs, four dives completed by HOV *Alvin*, and four dives by the dual-body

Jason/Medea ROVs. Substrate observations from the dive videos were sub-sampled in some cases such that all dives had observations recorded at approximately one-minute time intervals while the vehicles were traversing terrain, resulting in 6,081 substrate observations of the seafloor.

Twelve dives were annotated for primary (dominant) substrate at one-minute dive time intervals as part of detailed annotations for sessile fauna conducted for the DEEP SEARCH project. Five dives were annotated by NOAA OER staff using the same substrate types as DEEP SEARCH, but ensuring the decision criteria and substrate size thresholds followed CMECS. Six dives were annotated by staff at NOAA's National Centers for Coastal Ocean Science Deep Coral Ecology Lab for primary substrates using a simplified CMECS terminology along with additional comment notes to provide more detail. These annotations were done for different purposes by different observers, but were deemed general enough in nature to still be valid for the purposes of this paper without cross-validation between different observers. For all observations, the terminology used to describe the primary dominant substrate type was harmonized with the standard terminology for primary substrate units published in the Coastal and Marine Ecological Classification Standard (CMECS). **Table 4.1** shows how substrate class terminology from DEEP SEARCH was converted to CMECS unit terminology. **Figure 4.2** shows example video imagery stills of the common dominant substrate classes in the study area.

Table 4.1. Substrate classification terminology used by the DEEP SEARCH team and how it was translated into standard terminology used in CMECS. The table includes fields recommended in the CMECS crosswalking standard.

DEEP SEARCH Class	**Relationship to CMECS**	**CMECS Class/Subclass**	**CMECS Component**	**Confidence**	**Relationship Notes**
Live Scleractinian Coral	Nearly Equal (≈)	Coldwater Stony Coral Reef	Biotic	Certain	Live vs. dead coral cannot be described with CMECS substrate classes, the Biotic Component Group unit for live coral was used.
Dead Standing Coral-framework	Less Than (<)	Coral Reef Substrate	Substrate	Certain	CMECS unit is not as specific.
Coral Rubble	Equal (=)	Coral Rubble	Substrate	Certain	
Sediment	Greater than (>)	Fine Unconsolidated	Substrate	Somewhat Certain	Sediment in the DEEP SEARCH schema includes gravel classes. Anything smaller than cobble may be included, but gravel classes were rare in dive areas.
Sedimented Bedrock	Nearly Equal (≈)	Bedrock / Co-occurring element modifier Fine Unconsolidated	Substrate	Somewhat Certain	This class was used when the dominant substrate was clearly bedrock, but >50% had sediments thick enough to preclude most sessile reef-associated fauna.
Exposed Bedrock	Less Than (<)	Bedrock	Substrate	Certain	
Cobble	Nearly Equal (≈)	Cobble	Substrate	Somewhat Certain	Exact size thresholds unclear.

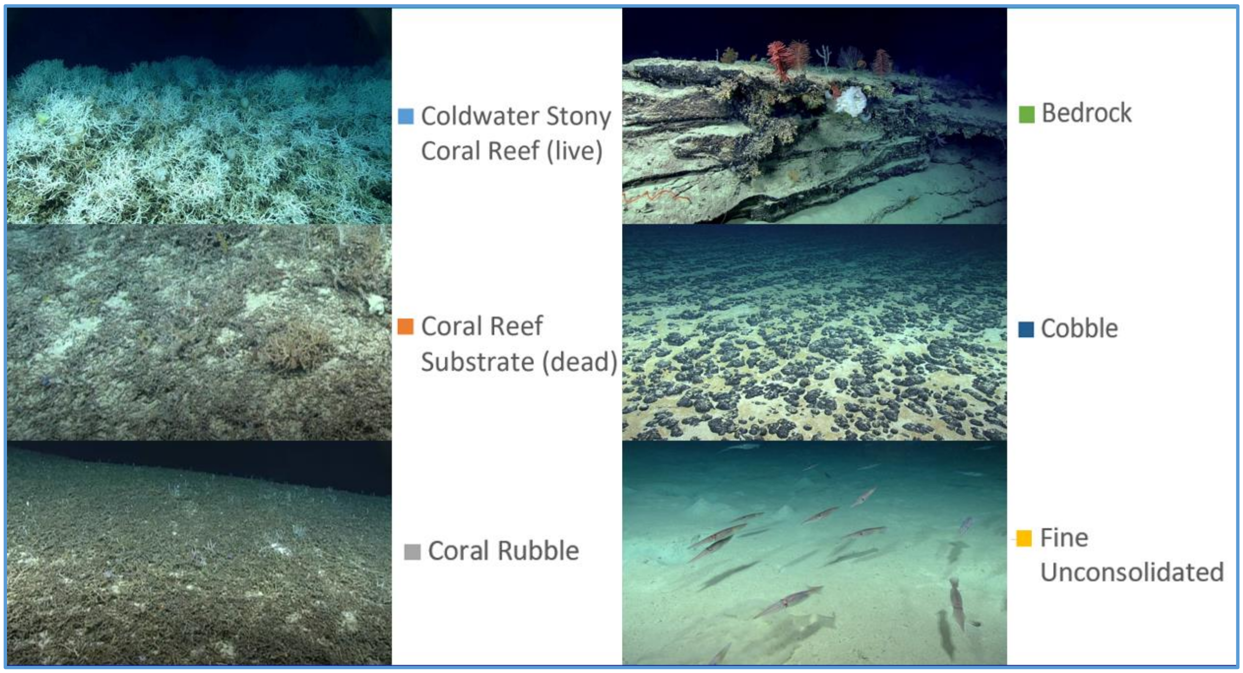

Figure 4.2. Primary (dominant) substrate classes used in the study. CMECS unit terminology is shown. The "coldwater stony coral reef" unit is a biotic component descriptor in CMECS, but was used in this study like a substrate class in order to differentiate living stony coral reef from dead standing coral-framework (dead stony coral skeletons not broken down into rubble).

Each substrate observation was recorded with longitude, latitude, and depth information enabling accurate georeferencing. Excel files containing the substrate data for each dive were imported into ArcGIS Pro v2.6.0 Pro as point feature layers. Each layer was then queried to select by attribute each unique combination of primary substrate class and landform type. The number of point observations for each combination of substrate class (up to seven class possibilities) by each landform type (up to five possibilities: slope, peak, ridge, flat, valley) was then entered into a separate Excel tracking sheet. Once these data were compiled for all 23 dives, total sums of substrate observations per landform class were computed and plotted as bar plots to summarize how substrate classes differed with landform type.

4.3 Results and Discussion

4.3.1 Extent and Geomorphic Characterization of the Cold-water Coral Province

Figure 4.1 shows the bathymetric synthesis of the whole study region, along with the polygon for the maximum extent of nearly continuous CWC mound features (yellow) and the minimum extent core area of continuous CWC features. The maximum extent polygon is 472 km long from north to south and up to 88 km wide from west to east. The area enclosed is 28,047 km^2 (6.9 million acres). The core area of dense CWC mounds in the minimum extent polygon is 248 km long by up to 35 km wide, encompassing an area of 5,179 km^2 (1.2 million acres). To put the size of these areas in perspective with other terrestrial protected areas in the U.S., the maximum extent is 3x larger than Yellowstone National Park and the minimum extent is larger than Grand Canyon National Park.

The geomorphic landform classification of the bathymetry data using the BRESS terrain analysis tool enabled the quantification of 59,760 individual peak features, providing the first overall estimate of the number of potential CWC mound features in the study region. Inspection of the peak landform class draped onto the bathymetry in QPS Fledermaus visualization software shows strong alignment with CWC mound peak features compared with expert interpretation. This correlation means that the vast majority of features classified as peaks are indeed likely to be CWC mound peaks in this particular setting. An example oblique 3D view of the landform classification results draped onto bathymetry is show in **Figure 4.3**.

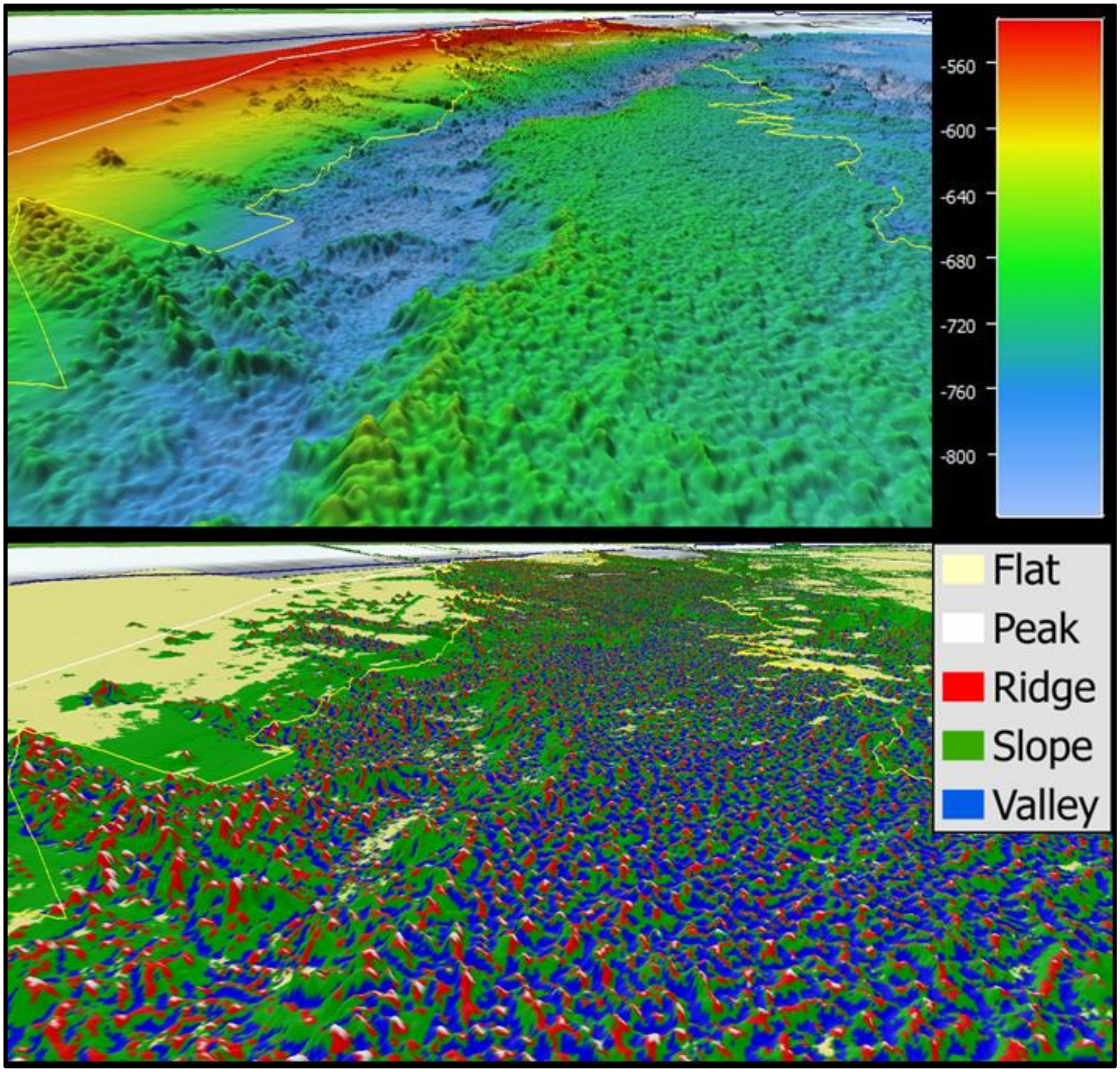

Figure 4.3. Oblique perspective 3D views of a section of the core area of dense mounds in the "Million Mounds" subregion. Bathymetry of mound features in meters (upper panel). Geomorphic landform classification draped onto the bathymetry (lower panel). Resolution of grids is 35 m, vertical exaggeration of 8x. The thin yellow line is the minimum extent polygon of continuous mound features, and the white line is the maximum extent polygon. Note the delineation of the white peak features from the rest of the CWC mounds to enable the enumeration of mounds and the calculation of mound relief metrics for each mound.

Cumulative areas were calculated for each of the five geomorphic landform classes: peaks (342 km^2), valleys (2,883 km^2), ridges (2,952 km^2), slopes (15,227 km^2), and flats (49,003 km^2). **Figure 4.4** provides a bar graph of these results. While flats make up the largest area, the other four classes collectively cover an area of 21,404 km^2 and comprise the complex CWC mound and steep scarp features in the region. The aggregated area of peak features alone covers an area 6x the size of the island of Manhattan in New York City, and the area covered by peaks and ridges together comprise an area larger than Yosemite National Park. Terrestrial protected area size comparisons are noted to prompt the reader to consider the ecosystem services provided by these important marine habitats at such a scale. A valuation of estimated ecosystem services for the Blake Plateau CWC mound province is beyond the scope of this paper, but the initial characterization provided here provides a basis upon which further assessment can be undertaken. For an example of an application of an ecosystem services valuation approach to a large marine ecosystem refer to Mayer et al. (2013).

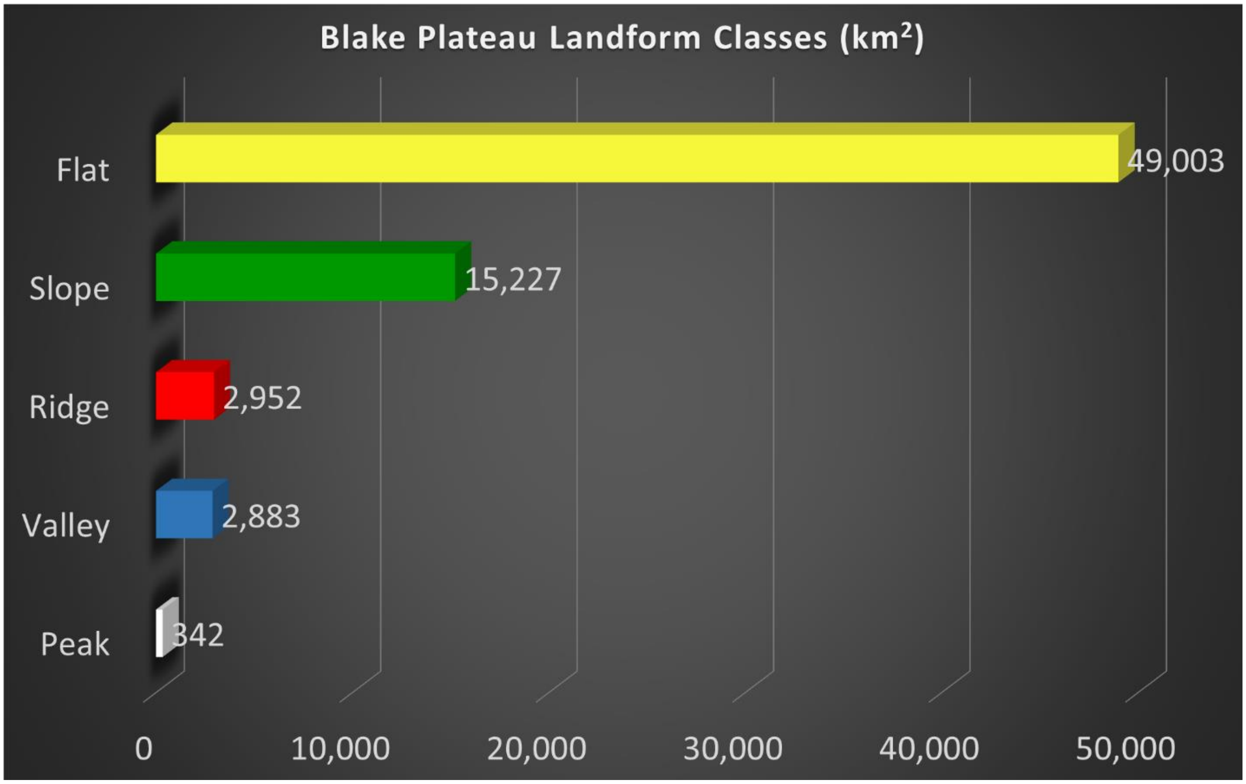

Figure 4.4. Bar plot showing the cumulative areas of the five geomorphic landform classes within the overall study region.

The value of developing and applying a user-parameterized terrain segmentation and classification approach for geomorphic characterization becomes readily apparent in a massive and complex CWC mound province such as described here. As evident from **Figure 4.3**, manually delineating these features in a consistent repeatable way with a comparable level of detail would not be possible. Another benefit of this approach is the transparency of landform classification methods. Once the model is set up with a few user-defined parameters tailored to the study area, the algorithms are based on a published mathematical terrain modeling approach instead of expert judgement. Results can, therefore, be replicated by other researchers given the same input data and model parameters. The transparency of the BRESS modeling approach also enables it to be applied to other CWC provinces for more consistent comparative analysis.

Standardization of methods is an inherent objective of this study. The feasibility of using the geomorphic landform classes in order to classify “geoform” units as part of the CMECS standard (FGDC, 2012) was evaluated, therefore **Table 4.2** provides a comparison of the landform units generated by this study versus the closest analogous geoform units in CMECS. Since CMECS is a dynamic content standard intended to be revised and updated over time, new provisional units may be proposed. New potential provisional geoform units are listed in column three of **Table 4.2.** If the proposed units existed in CMECS, the landform classes from this study could largely be transitioned 1:1 to a standardized terminology scheme.

Table 4.2. Comparison of the geomorphic landform units classified in the current study to existing CMECS geoform unit terminology.

BRESS Landform Units from Study	CMECS Geoform Units Applicable to Study Area Tectonic Setting: Passive Continental Margin Physiographic Setting: Borderland	Potential New Provisional Geoform Unit
Peak	Closest analogue is "Knob" but it is of geologic origin, not biogenic)	• Mound Peak (if CWC mound) • Scarp Peak (if on scarp feature)
Ridge	Ridge (1:1 crosswalk)	• Mound Ridge (if CWC mound)
Valley	Valley (current definition would need expansion beyond continental shelf)	• Mound Valley (if adjacent to CWC mound) • Scarp Valley (if at base of scarp feature)
Slope	Slope (1:1 crosswalk)	• Mound Slope (if CWC mound)
Flat	Flat (1:1 crosswalk)	--
	Scarp/Wall Fault Scarp (Level 2 option) Erosion Scarp (Level 2 option)	--
	Deep/Cold-water Coral Reef • Biogenic Deep Coral Reef (living) (Level 1 or 2 option) • Deep Coral Carbonate Mound (lithoherms) (Level 1 or 2 option) (Note that this unit is comprised of "peak," "ridge," and "slope" landform units from the current study)	New Level 2 units under CWC Reef • Mound Peak • Mound Ridge • Mound Slope • Mound Valley

The high resolution bathymetric synthesis and the objectively generated full-coverage spatial geomorphology layers generated by this study offer strong potential as a valuable input into coral habitat suitability models of the region. Many species of deep sea corals show particular affinities for high-relief hard substrate features found on mound peaks and ridges. Utilizing fine scale delineations of these features as model inputs - or weighted spatial filters for fine tuning output probabilities - may result in more accurate models with improved predictive performance. Given the recent multifold increase in availability of high resolution full coverage multibeam data for increasingly larger regions of the deep sea (and future trends in this direction), the quality of the input bathymetric data into habitat models, and the corresponding derived terrain spatial layers associated with them (e.g. slope, aspect, rugosity, benthic position index, etc.) is rapidly improving.

It is interesting to note that Paull et al. (2000) postulated that there may be as many as 40,000 CWC mounds in the area of seafloor underneath the Gulf Stream in the Straits of Florida and inner Blake Plateau with coral-bearing structures covering over 400 km^2. The data presented in this paper covers much of the geographic region Paull described and enumerates 59,760 likely CWC mound structures with a collective peak area (of mostly coral-related substrates) covering 342 km^2. Paull's estimates were based on an assumption of one mound structure every 3 km^2 (0.3 peaks/km^2), whereas this paper has calculated an average peak density of 0.8 peaks/km^2 for the whole study region, and an average of 4.8 peaks/km^2 for the Million Mound region. These comparisons show that these earlier coarse estimates of potential mound habitat were reasonable (especially based on very limited mapping information) and ultimately conservative in light of what has recently been revealed by additional mapping expeditions with the benefit of multibeam sonars.

4.3.2 Geomorphic Diversity of Subregions

The complex geomorphology of eight subregions is characterized in this section qualitatively with geomorphic "fingerprints" and quantitatively by measurements of mound density and vertical relief. The median mound relief for the entire study region was 14 m, with individual mound features ranging 3-178 meters above the adjacent seafloor. **Figure 4.5** provides an overview map of the landform classification results for the entire study area and highlights the locations of the featured subregions. Subregions are labeled A-H and provided an informal site name for the purposes of this study. Informal names do not correspond to any officially named features in the region. Richardson and Million Mounds are colloquial names used by some scientists and managers in the region.

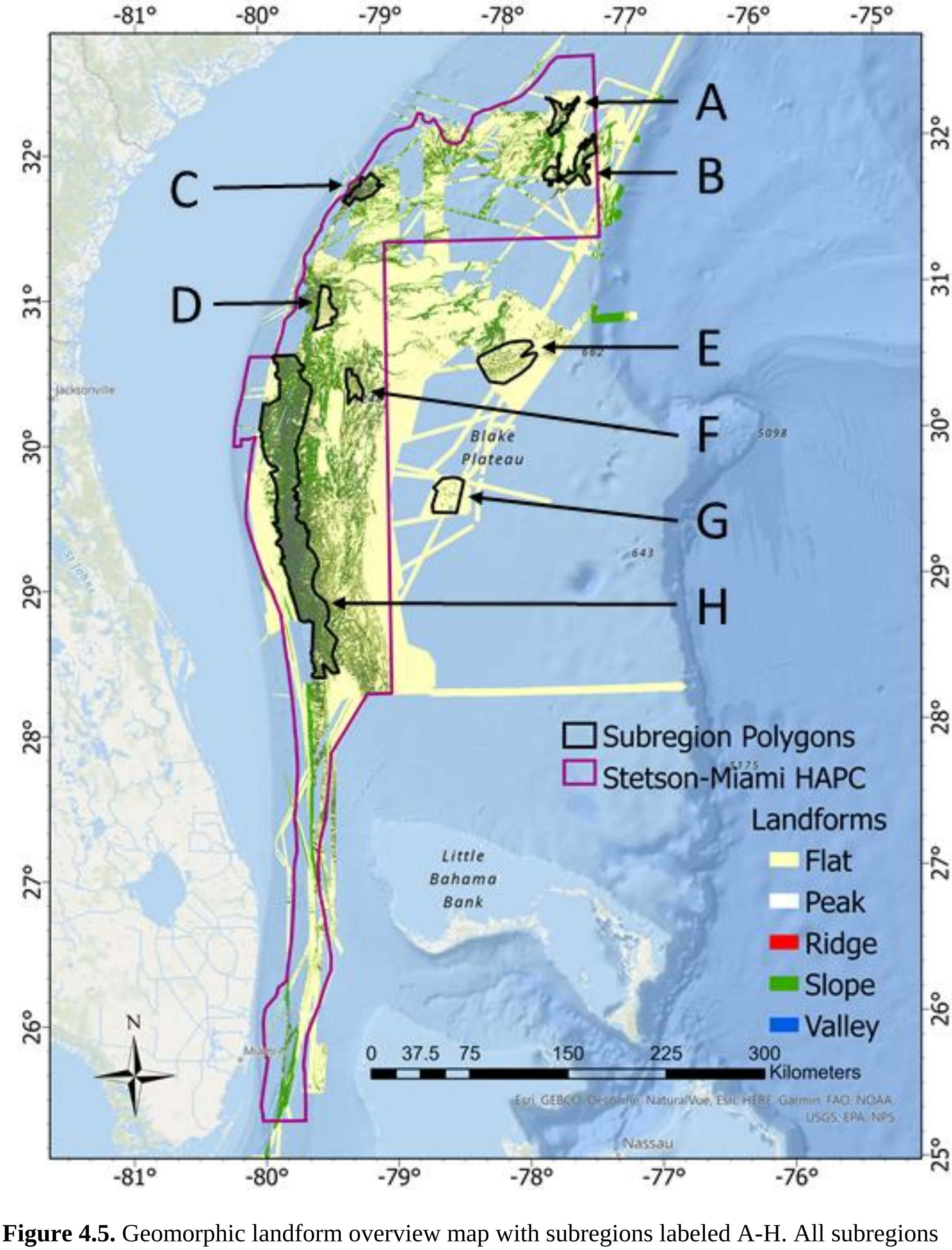

Figure 4.5. Geomorphic landform overview map with subregions labeled A-H. All subregions contain CWC mound features. Note how the landform map provides a strong immediate visual contrast between flat areas and complex terrain.

Maps of each subregion are provided in **Figures 4.6 – 4.9**. The left panels display graduated symbols of mound relief overlain on hillshaded bathymetry, with each circle representing an individual mound feature. The larger the red circle, the greater the vertical relief of the mound. These plots quickly provide a visual display of mound densities and relative relief across the bathymetry grid. The right panels display the geomorphic landform classes as draped on the bathymetry.

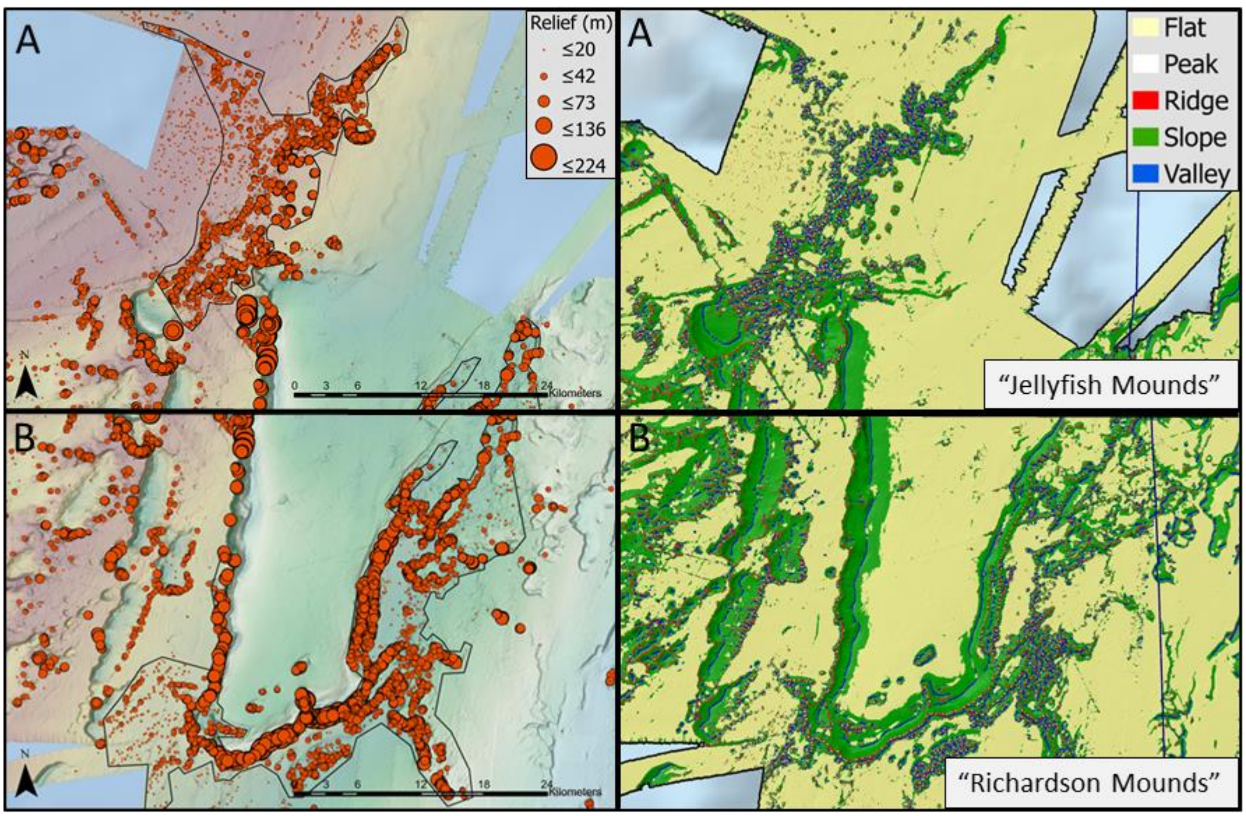

Figure 4.6 Maps showing graduated vertical mound relief symbols (left panels) and landform classifications draped on bathymetry (right panels) for Jellyfish Mounds and Richardson Mounds. Letters in the top left corner correspond to the letters in the Figure 4.5 overview map. Black outlines in the left panels are the polygons delineated in ArcGIS Pro v2.6.0 for the purpose of quantifying and contrasting metrics about the nature of mounds in each subregion. Blue lines in the right panels show the current boundary of the Stetson-Miami HAPC.

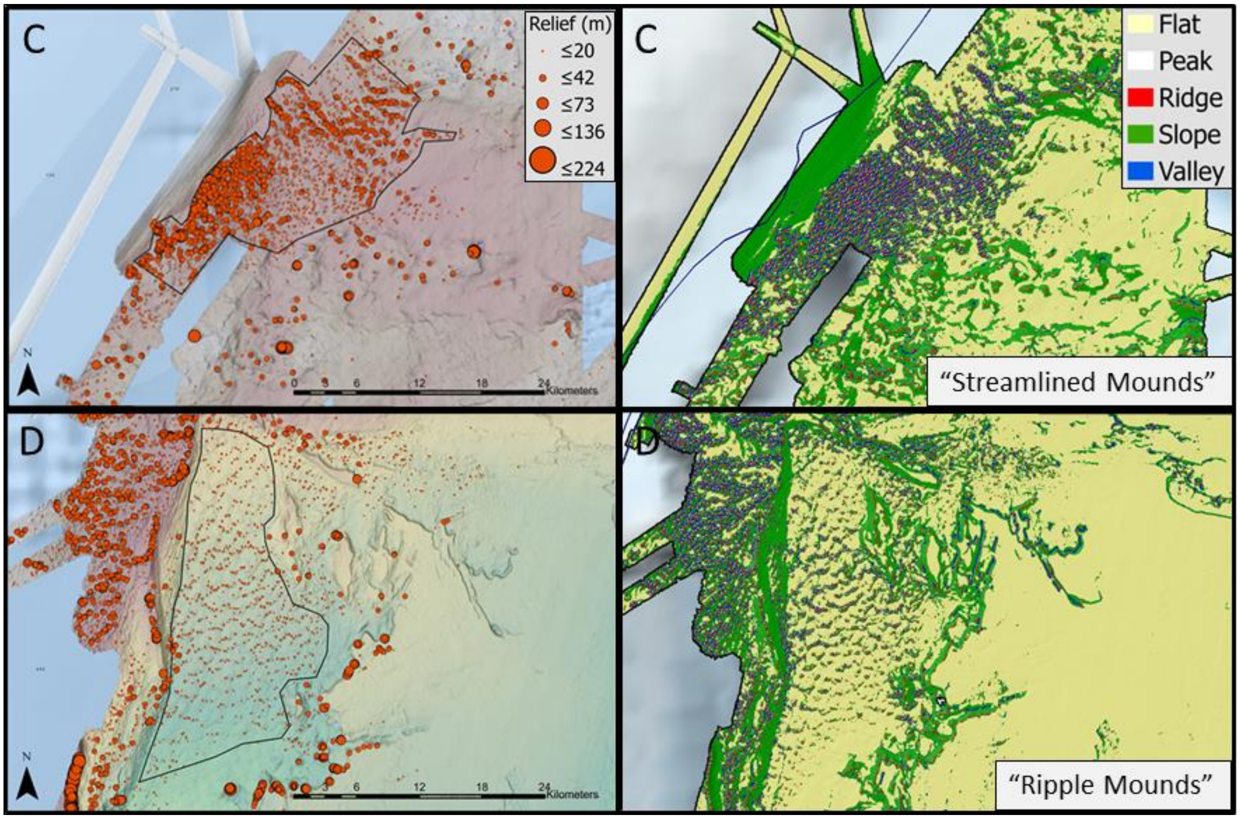

Figure 4.7. Maps showing graduated vertical mound relief symbols (left panels) and landform classifications draped on bathymetry (right panels) for Streamlined Mounds and Ripple Mounds. Letters in the top left corner correspond to the letters in the Figure 4.5 overview map. Black outlines in the left panels are the polygons delineated in ArcGIS Pro v2.6.0 for the purpose of quantifying and contrasting metrics about the nature of mounds in each subregion. Blue lines in the right panels show the current boundary of the Stetson-Miami HAPC.

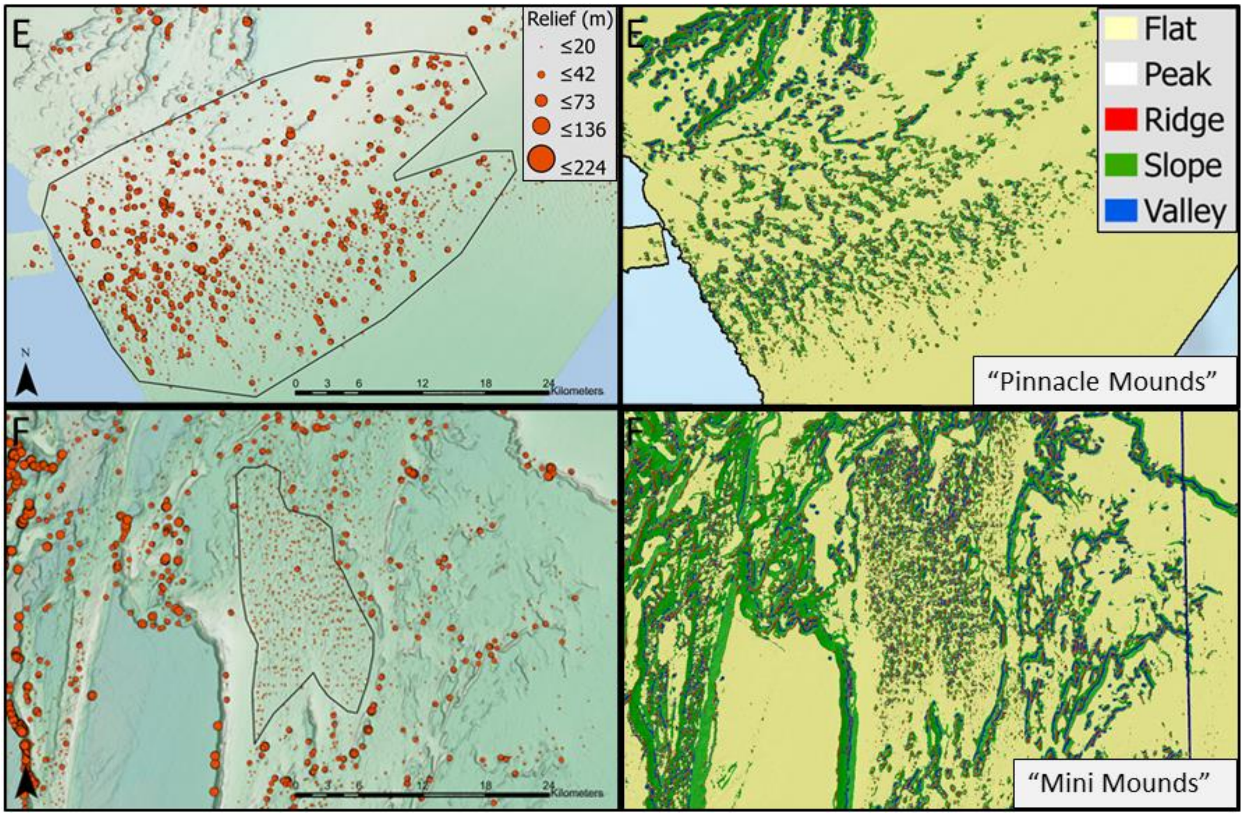

Figure 4.8. Maps showing graduated vertical mound relief symbols (left panels) and landform classifications draped on bathymetry (right panels) for Pinnacle Mounds and Mini Mounds. Letters in the top left corner correspond to the letters in the Figure 4.5 overview map. Black outlines in the left panels are the polygons delineated in ArcGIS Pro v2.6.0 for the purpose of quantifying and contrasting metrics about the nature of mounds in each subregion. Blue lines in the right panels show the current boundary of the Stetson-Miami HAPC.

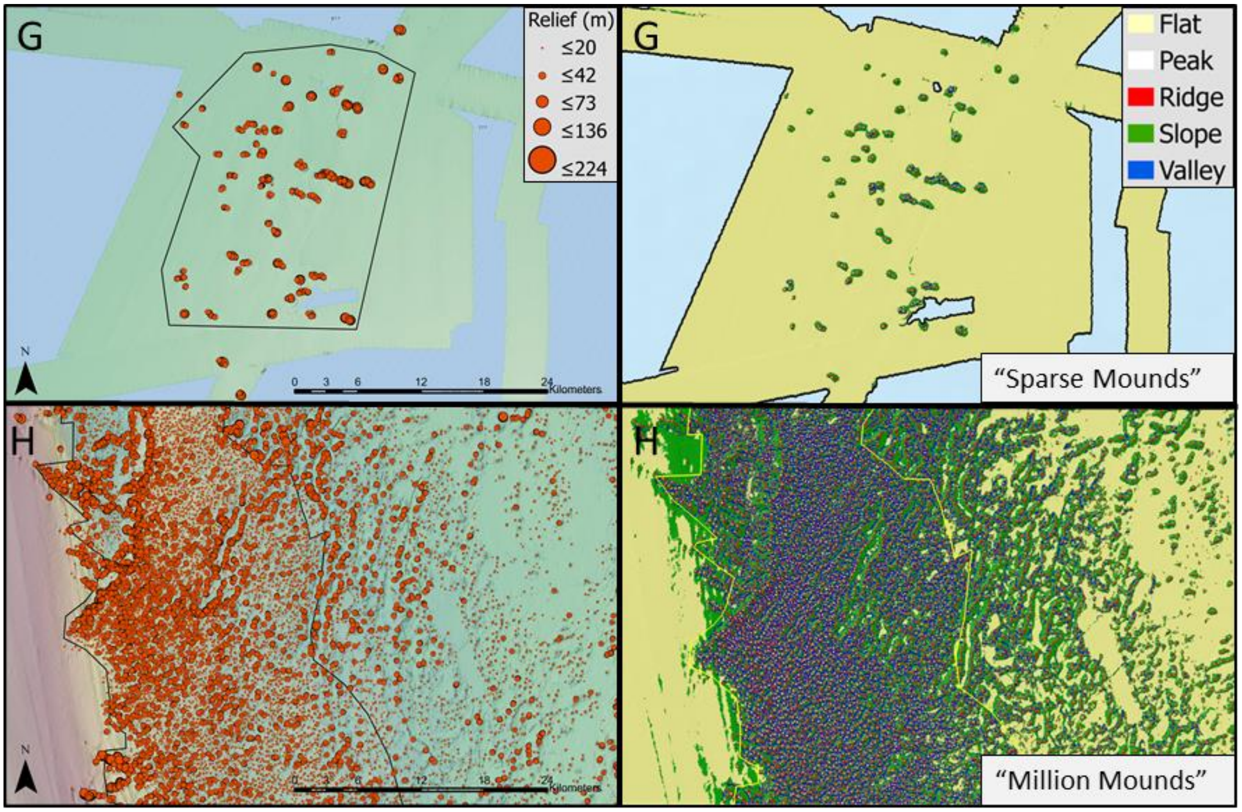

Figure 4.9. Maps showing graduated vertical mound relief symbols (left panels) and landform classifications draped on bathymetry (right panels) for Sparse Mounds and Million Mounds. Letters in the top left corner correspond to the letters in the Figure 4.5 overview map. Black outlines in the left panels are the polygons delineated in ArcGIS Pro v2.6.0 for the purpose of quantifying and contrasting metrics about the nature of mounds in each subregion. The yellow line in the lower right panel is the core area of dense mounds used to define the minimum extent of continuous coral mound features.

A review of **Figures 4.6-4.9** provides some interesting qualitative insights into the diversity of CWC mound morphologies in this region. In **Figure 4.6** both Jellyfish and Richardson Mounds show obvious patterns of high relief mound features formed at the tops and edges of the steep scarps found in that subregion. Jellyfish Mounds are located just northwest of Richardson Mounds. The linearity and continuity of the mound features along the distinct ridges found at the top of the scarp features is different from other parts of the Blake Plateau where mound features do not form in lines and have more space between each other.

Streamlined Mounds in **Figure 4.7** shows extremely high mound densities and clear directionality in mound orientation. Mounds are elongated along the southwest-to-northeast direction, indicating a very likely strong morphology-shaping influence of the Gulf Stream current in this area. In stark contrast, the Ripple Mounds subregion in **Figure 4.7** shows mounds clustering along widely spaced gently curving crest patterns. As shown in a profile of these features (**Figure 4.10**), the mound features are found on minor topographic highs spaced roughly 800-2000 m apart. It is unclear if this pattern of mound development is a result of the corals populating existing minor crests in the bathymetry with favorable substrates, or if the pattern was created via spatial self-organization through scale-dependent feedbacks as theorized by van der Kaaden et al. (2020). This particular pattern is unique to this subregion for the areas mapped thus far on the Blake Plateau.

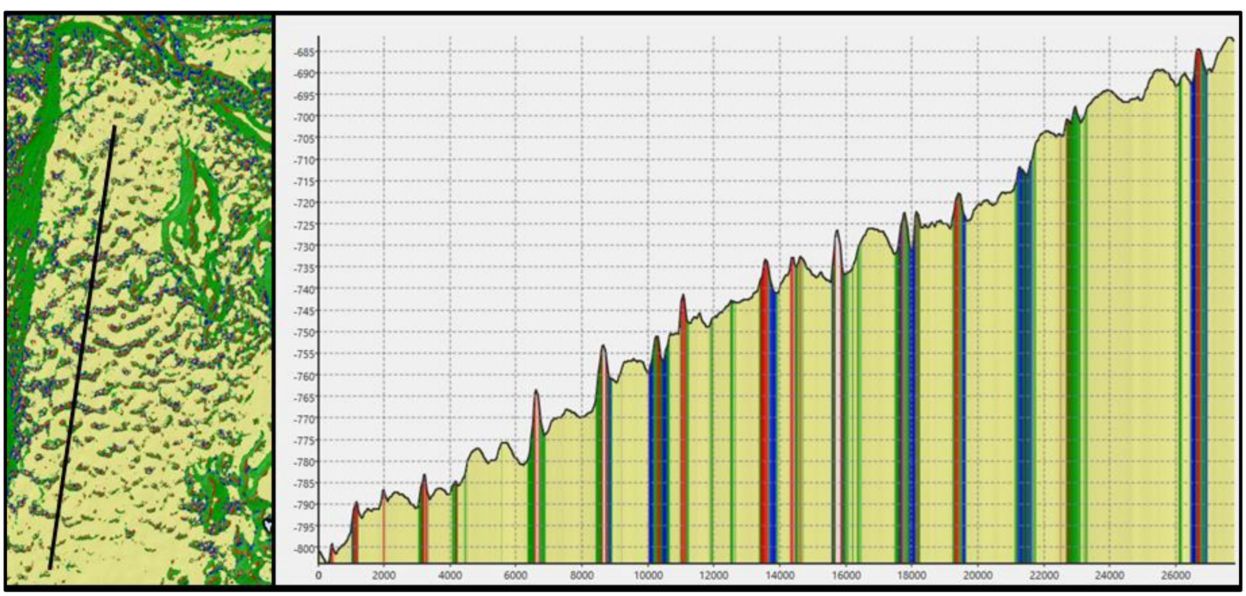

Figure 4.10. Profile view of landform features draped on bathymetry for the Ripple Mounds subregion (area "D" in **Figure 4.5**). The black line on the left shows the profile transect in planview. The profile on the right has vertical exaggeration of 100x, units are in meters.

Another unique pattern is found in the Mini Mounds subregion (area “F” in overview **Figure 4.5**) as shown in **Figure 4.8**. The mounds here are remarkably uniform in spacing and in their diminutive height, with an average vertical relief of 10 meters. The Sparse Mounds subregion (area “G”) exhibits its own unique characteristics, showing widely spaced but prominent mounds in an otherwise very flat region of the Blake Plateau. There is no surface terrain expression of favorable underlying geology in the Sparse Mounds area. This observation is in contrast to other subregions, subregions such as Jellyfish and Richardson that have CWC mounds on top of underlying geologic features that must have provided favorable circumstances to sustain the growth of stony corals. Additional analysis of sub-bottom profiler sonar data in this area may provide useful insights.

Sparse Mounds and Pinnacle Mounds (subregion “E” in overview **Figure 4.5**) are large newly discovered regions of CWC mounds located outside of the existing Stetson-Miami HAPC protection zone. **Figure 4.11** is provided to show a 3D perspective view of the bathymetry and an example profile view of the distinct pinnacle morphology of the mounds in this subregion.

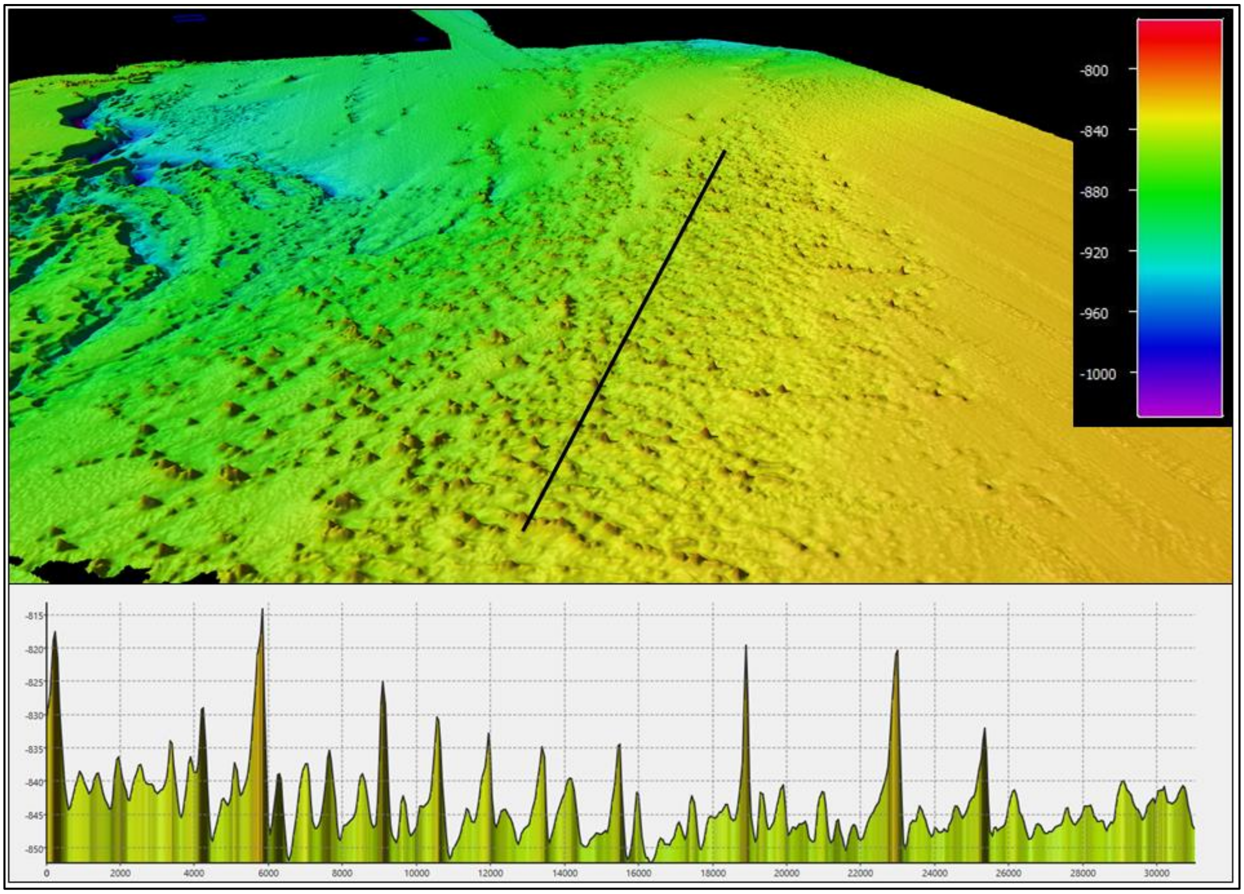

Figure 4.11. 3D oblique perspective view of the 35 m resolution bathymetry for the Pinnacle Mounds subregion (top panel). The bottom panel shows a profile of mound relief with 180x vertical exaggeration corresponding to the black line in the top panel.

Within each of the eight subregions the following metrics were calculated in ArcGIS Pro v2.6.0 to characterize CWC mound features: number of mound peaks, peak density (number of peaks per km^2), area of peak landforms, areas of ridge landforms, and mound peak minimum and maximum depths. Additional statistics were also calculated specific to CWC mound feature relief from the surrounding terrain: range, minimum, maximum, mean, median, and standard deviation. These values were then aggregated into a table of statistics from all subregions to enable comparisons (**Table 4.3**).

Table 4.3. Comparison of morphology metrics for the 8 CWC mound subregions evaluated. Standout numbers are shown in tan colored cells for emphasis.

Mound Sub-Region Name	# of peaks	Peak Density (#/km^2)	Area of Peaks (km^2)	Area of Ridges (km^2)	Mound Relief Metrics						Mound Peak Min Depth (m)	Mound Peak Max Depth (m)
					Range (m)	Min (m)	Max (m)	Mean (m)	Median (m)	Std. Deviation (m)		
A. Jellyfish Mounds	783	3.2	6.2	25.6	99	3	102	30	26	18.4	491	662
B. Richardson Mounds	1,210	2.6	8.0	43.4	157	3	160	44	35	32.7	656	861
C. Streamlined Mounds	1,331	4.5	7.8	47.3	73	4	77	19	18	8.7	440	562
D. Ripple Mounds	647	2.0	3.1	21.9	24	4	28	10	10	3.3	659	802
E. Pinnacle Mounds	1,271	1.4	8.7	43.6	50	3	53	18	16	8.3	785	894
F. Mini Mounds	387	1.9	1.5	24.6	19	4	23	10	9	3.1	799	846
G. Sparse Mounds	168	0.3	1.4	5.5	47	7	54	34	33	7.6	758	815
H. Million Mounds	24,819	4.8	151.5	853.0	100	3	103	20	17	10.0	356	918
Entire Region	59,760	0.8	342	2952	221	3	224	20	17	13.9	71	2688

Within the overall study region 59,760 individual peak features were identified. Mound relief within subregions ranged from 3-224 meters above adjacent seafloor within the 420 m radius used to calculate relief. The Million Mounds subregion polygon (row H) contained 24,819 individual mound features – 42% of the total number of mounds mapped in the entire region. Peak density (4.8 mounds/km^2), and the areas of peaks (151.5 km^2) and ridges (853 km^2) were also greatest in Million Mounds. Streamlined Mounds had an almost equivalent peak density (4.5 mounds/km^2), and is clearly a distinctive area in this respect. Million Mounds supports the largest depth range of coral mound features, with some mounds as shallow as 356 m and as deep as 918 m.

The Richardson Mounds subregion is a distinctive area in terms of mound relief metrics, containing the largest range, max, mean, median, and standard deviation values. Mound peak relief maximum, mean, and median values for each subregion are plotted in **Figure 4.12**. The 57 m difference in maximum relief between Richardson and the next highest value (Jellyfish Mounds) appears to be significant, but may be somewhat of an artifact of the relief calculation method. It has already been noted that mound features located at the top of very steep scarp features show high terrain relief, so the maximum values are subject to significant change depending on the polygon subregion location and inclusion of specific mound features. High relief values alone do not provide insight into the proportion of relief due to the elevation of the underlying biogenic structure (formed by stony coral skeletons and sediment deposition over long time scales) versus the base geology that any given mound formed upon. Therefore, the maximum relief values should be interpreted cautiously, while still providing some utility in terms of comparing subregion values. Million and Jellyfish Mounds had essentially the same maximum values, as did Sparse and Pinnacle mounds. Mini Mounds had the lowest maximum relief.

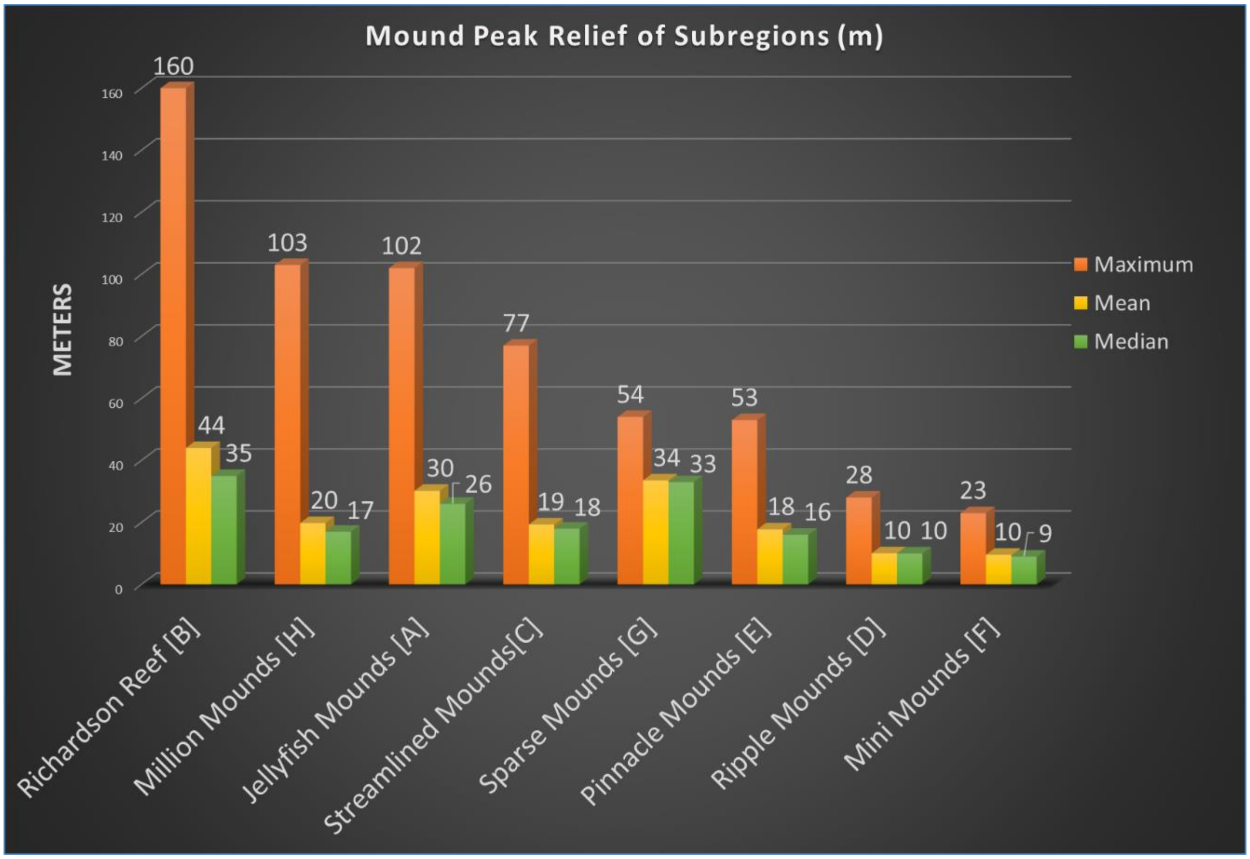

Figure 4.12 CWC mound peak relief of eight subregions based on the maximum vertical change in any of the eight directions up to 420 m radius surrounding a peak landform feature. The maximum single vertical relief value within a subregion is shown in orange. Yellow bars represent mean values and green bars represent median values of all peaks in the subregion.

Examination of the mean and median relief numbers shows that Richardson Mounds still has the highest values, but is closely followed by Sparse Mounds. It is apparent that while the Sparse Mounds subregion does not have a great number of mounds, the mounds that are present are on average some of the largest in the region, with a mean value of 34 and median value of 33. It is worth noting here that the one ROV dive completed thus far to one of the mounds in Sparse Mounds documented large areas of coral rubble, dense live *Lophelia*, and patches of *Madrepora* corals – documenting the high biological importance of these CWC mound features located outside of the current HAPC boundary. The close or matching values between mean and median numbers at all subregions except for Jellyfish and Richardson Mounds reveals a largely symmetrical distribution of relief within each of these subregions. Jellyfish and Richardson Mounds show a more skewed data distribution with some high relief outliers. This result again indicates that the large scarps in these regions likely exaggerate the high relief values, and that the values presented here should not be confused with the purely biogenic thickness component of the CWC mounds. More evidence is needed to understand if the biogenic mound component to the relief in these subregions is larger than in other areas. Analysis of sub-bottom sonar data, seismic reflection data, and drilling cores of mound features could provide substantially more insight into mound composition and thickness.

The depth values for mound peak features within each subregion are displayed in **Figure 4.13**. The greatest variation in mound depths is within the Million Mounds area, spanning a range of 562 meters. Both the shallowest (356 m) and deepest (918 m) mound depths are also found in the Million Mounds subregion. All other subregions have considerably narrower depth ranges. Sparse Mounds and Mini Mounds had the smallest ranges, with mound peak depths that occur at uniform depths within a range of 57 and 47 m, respectively. Pinnacle, Sparse, and Mini Mounds subregions were the deepest overall areas with their shallowest mound peaks at 785 m, 758 m, and 799 m, respectively. All of the mound peaks in the sub-regions fall within the depth range of about 350 to 900 m.

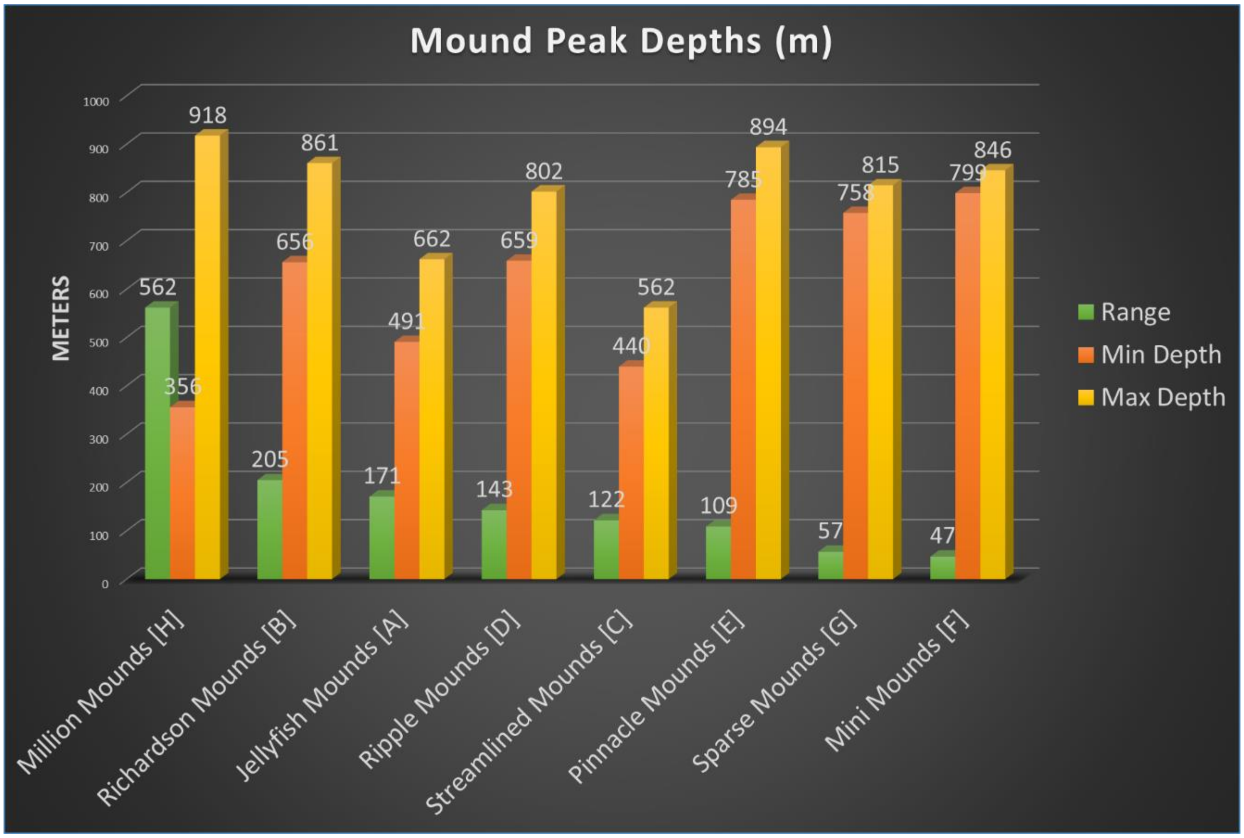

Figure 4.13. Bar plot showing depths of CWC mound peak features in each subregion. The range of peak depths is shown in green, minimum depths are shown in orange, and maximum depths are shown in yellow. The subregions are ordered by largest to smallest depth range values moving from left to right along the x-axis.

4.3.3 Substrate Classes of Landform Types

Substrate observations recorded from video data from 23 submersible dives at approximately 1-minute intervals (n = 6,081 substrate annotations) were harmonized with the Coastal and Marine Ecological Classification Standard (CMECS) and used to assess the substrate character within classified landforms. Bar plots of the results are shown in **Figure 4.14** and **Figure 4.15**. As shown in **Figure 4.14**, slope features had the greatest number of overall observations, followed by ridges and peaks. Given that the CWC mound features were the target of most dives, it is logical that most of the observations occurred traversing up the slope, followed by exploration of the ridges and peaks of the mounds. Flat and valley landforms only represent 9% and 6% respectively of the overall observations.

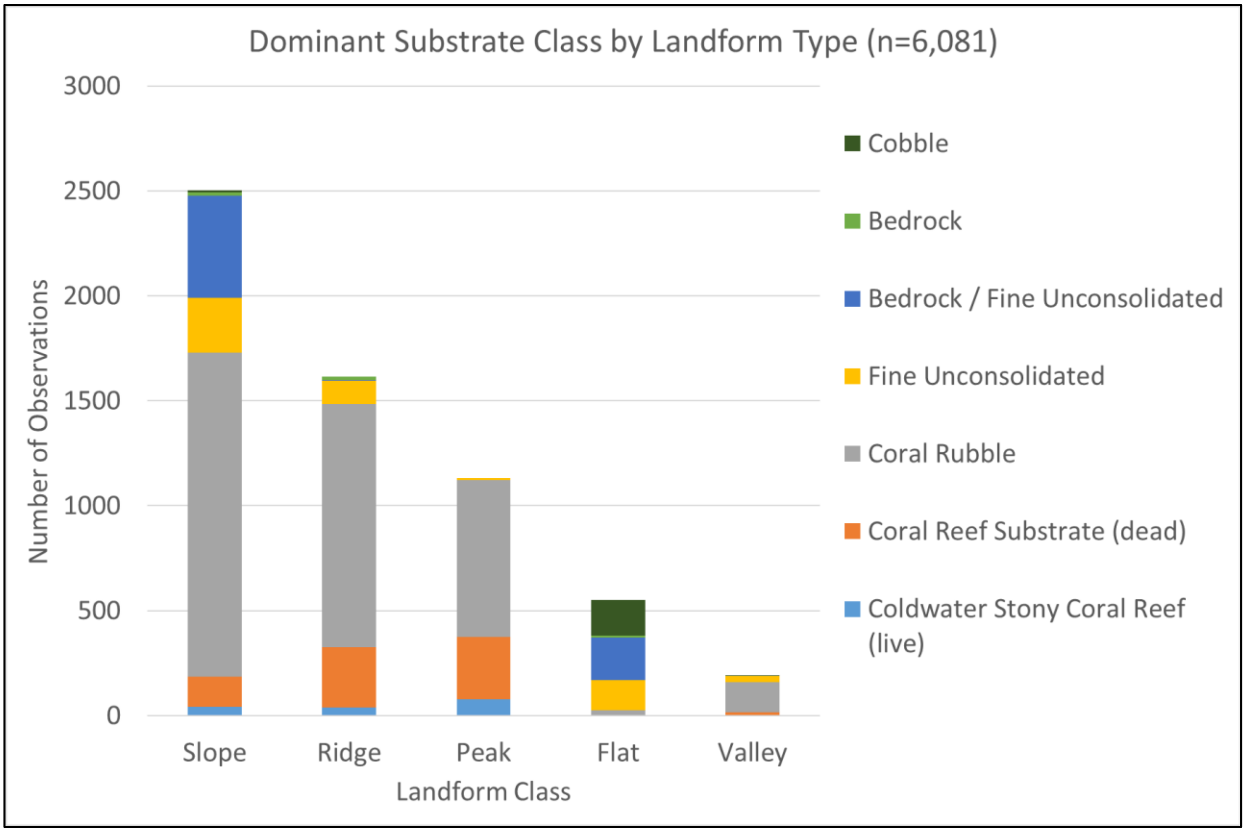

Figure 4.14. Plot of primary substrate types observed for each landform class based on interpretation of submersible video data. The y-axis represents the number of substrate observations aggregated for each landform class.

As evident from the cumulative plot shown in **Figure 4.15**, Coral rubble was found to be the dominant substrate component within the peak (66%), ridge (72%), and slope (62%) landforms, thereby validating the interpretation of these bathymetric features as CWC mounds. This result was true even on mounds with as little as 10 meters of average vertical relief from the surrounding seafloor, as documented for the Ripple Mounds and Mini Mounds subregions.

Live stony coral reef was found exclusively on peaks (7%), ridges (2%), and slopes (2%). Dead coral reef substrate (i.e. dead standing coral-framework) is shown in orange and was also found almost exclusively on peaks (26%), ridges (18%), and slopes (6%) - with more standing framework typically found in the higher relief areas. Unconsolidated sediments (shown in yellow) are mostly absent from peaks (1%), but do occur sporadically on ridges (7%) and slopes (10%). The substantial coral rubble component in the valleys (76%) may indicate that rubble is conveyed downslope by strong currents, biodegradation, and gravity to accumulate in certain valley features adjacent to mounds. It is notable that cobble (dark green, 31%) and bedrock (light green and dark blue classes, 2% and 37% respectively) were major components of the flats explored – evidence of the hard-bottom habitats in the region. The majority of bedrock observed was covered in fine sediments (>50%) as a co-occurring element (CMECS class bedrock / fine unconsolidated).

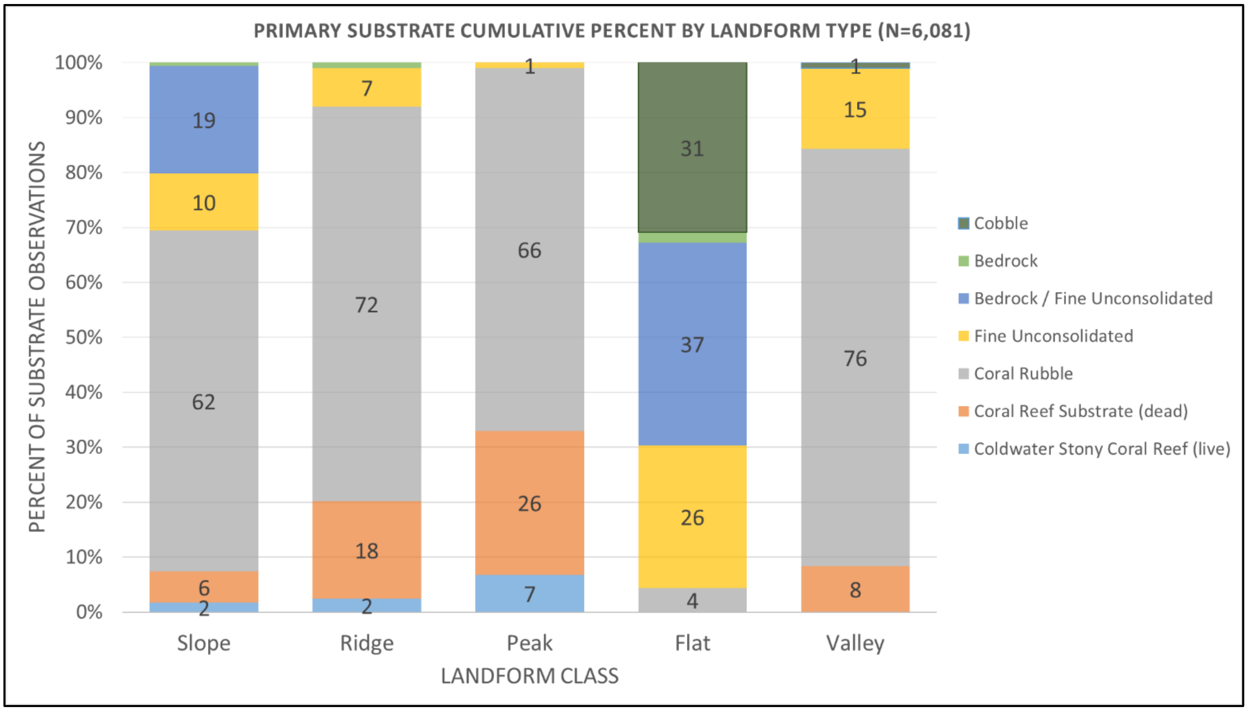

Figure 4.15. Plot of primary substrate types observed for each landform class based on interpretation of submersible video data. The y-axis represents the cumulative percent of substrate observations aggregated for each landform class.

The “rubble” class in this study should not be interpreted as corals damaged by human activities. Rubble substrate in the context of this study area occurs naturally as a result of the gradual breakdown of dead coral framework. Coral rubble can support high faunal diversity (Roberts et al., 2009), and is therefore an important marine habitat. Direct evidence of damage to coral and rubble habitats was not a component of this study. Numerous studies have clearly documented the sensitivity of CWC mound habitat (including rubble) to bottom-contact fishing practices or other human activities (e.g. Fosså et al., 2002; Grehan et al., 2005; Koslow et al., 2000). The substrate data in this study was methodically translated to CMECS terminology, with the intention that this will improve the longevity and usefulness of the data in the longer term.

4.4 Conclusions

This study demonstrated the value of applying an objective automated terrain segmentation and classification approach to geomorphic characterization of a highly complex CWC mound province. Manual delineation of these features in a consistent repeatable way with a comparable level of detail would not have been possible. As inevitably vaster regions of the oceans become mapped and explored, and the technological capability to map extensive seafloor features in high resolution with autonomous underwater vehicles (AUVs) expands, the importance of semi-automated classification approaches will only increase. Reliance solely on manual delineation and expert judgment is not a practical approach in these circumstances, and the inability to reproduce results and standardize methods across large ocean regions further supports the need for standardization or at least transparency in methodologies and terminology. The methods used in this study provide a pragmatic standardized approach for identifying, characterizing, and quantifying CWC mound-forming habitats and could be applied to other CWC provinces to enable more direct comparisons among geographically diverse settings.

The multibeam sonar bathymetric compilation and corresponding geomorphic landform maps generated by this study document what appears to be the most extensive CWC mound province thus far discovered. Nearly continuous CWC mound features span an area up to 472 km long and 88 km wide, with a core area of high density mounds up to 248 km long by 35 km wide. A total of 59,760 individual peak features were delineated, providing the first estimate of the overall number of potential CWC mounds mapped in the region to date. Five geomorphic landform classes were mapped and quantified: peaks (342 km^2), valleys (2,883 km^2), ridges (2,952 km^2), slopes (15,227 km^2), and flats (49,003 km^2).

CWC mound spatial distribution, density, vertical relief, and morphology varied greatly among subregions of the Blake Plateau. The median mound peak relief above surrounding seafloor for the entire study region was 14 m, with individual mound features in analyzed subregions ranging between 3-178 meters in vertical relief. Two large areas containing prominent and numerous CWC mounds were mapped in 2018 and 2019 that exist outside the present-day Stetson-Miami Habitat Area of Particular Concern. The northern area has 1,271 mound features and the southern area has 168.

The relationship between CWC mound size and flow hydrodynamics is complex and in need of additional research (Cyr et al., 2016; Soetaert et al., 2016), with important ramifications for the suitability of mounds for supporting stony coral growth and associated biota. The CWC mound relief spatial layers and summary statistics generated by this study can be used to target study sites for assessing hydrodynamic relationships with CWC mounds of diverse sizes across the Blake Plateau province.

The quantification of mound landform features provides a more robust basis to assess the significance of the ecosystem services provided by this major CWC province. Characterization of the Blake Plateau CWC mound province extent and geomorphic diversity is of direct relevance to marine resource managers charged with implementing ecosystem-based management approaches and protecting vulnerable seafloor habitats from potentially harmful human impacts.

Ground-truth for the geoform analysis was provided by direct substrate observations from 23 submersible dive videos that revealed coral rubble to be the dominant substrate component within the peak, ridge, and slope landforms explored, thereby validating the interpretation of these bathymetric features as CWC mounds. These results infer that it is reasonable to expect about 99% of classified mound peak areas and 92% of classified mound ridge areas to a have dominant substrate type that is CWC-related (coral rubble, dead coral reef substrate, and a small component of live cold-water stony coral reef). This has important implications for the collective ecological value of this CWC mound province given the proven linkages between coral habitat (live and dead) and the benthic and pelagic communities shown to be associated with them. These CWC-based habitats support rich communities of associated invertebrates and fishes in the Blake Plateau region (Reed et al., 2006; Ross, 2006; Ross and Quattrini, 2007). Submersible dive video data is biased towards under-sampling of the substrate characteristics of flat and valley features (9% and 6% respectively of the overall substrate observations), and therefore the data presented in this study for these geomorphic features may not be adequately representative of these habitats.

The application of the Coastal and Marine Ecological Classification Standard (CMECS) in deep sea environments is still evolving, and recommendations for interim provisional units were provided for the geoform component of the standard. The existing substrate classification units worked well for this study.

The extent and nature of CWC mounds characterized in this study should be compared with the other largest reported CWC mound and reef areas discovered thus far. Røst Reef in Norway has previously been recognized as the largest known CWC (*Lophelia*) reef, with an extent of 35 km x 3 km wide (Fosså et al., 2005; ICES, 2002) and covering an area of approximately 100 km^2 (WWF, 2020). The Mauritanian CWC mound province spans a nearly continuous line of mound features 400 km long, but with a narrow width and an unreported total area of coverage (Weinberg et al., 2018). The West Florida slope mounds reported by Reed et al. (2006) span an area of 230 km long by 10 km wide. The Northern Argentine Mound Province is estimated to cover an area at least 2000 km^2 (Steinmann et al., 2020). In comparison with these published studies, the core area of dense CWC mounds in the minimum extent polygon delineated in this study for the Million Mounds subregion alone covers a nearly continuous area of 5,179 km^2 and is larger in extent than any other continuous CWC mound or reef province yet discovered and published in scientific literature.

While the Blake Plateau region has long been recognized as one of the world's most significant CWC mound areas, its impressive extent can be more fully appreciated in light of the recently collected mapping data presented here. Given that some large regions of the Blake Plateau are still yet to be mapped with multibeam sonars, additional CWC habitats are sure to be revealed.

Acknowledgements:

The author would like to thank Ryan Gasbarro and Dr. Erik Cordes for providing detailed substrate annotations for twelve submersible dives used in the study for ground truth characterization of substrate types. Dr. Mashkoor Malik, Kasey Cantwell, and Matt Dornback provided substrate annotations for five ROV dives completed by *Deep Discover*/*Seirios* ROVs.

Chapter 5

Conclusion

The central premise of this thesis was to synthesize geomorphological elements of large regions of the deep ocean seafloor to establish standards of characterization for ecosystem-based habitat classification. The approach was to apply semi-automated characterization techniques on seafloor bathymetric data that were originally collected for other purposes. The purpose of generating these maps is ultimately to be useful for informing ecosystem-based management of large marine regions. While seafloor classification techniques for habitat classification have been applied in shallow water and generally over more local regions, these techniques have never before been applied at continental-margin scales in such deep water.

In Chapter 2 pragmatic methods were developed and applied to a case study of a seamount feature. Chapter 3 utilized insights from the case study and scaled the methods for systematic geomorphic classification to a dramatically larger region spanning the continental shelf break to the abyssal plains, from Canada to Florida. Results of Chapters 2 and 3 effectively validated the first two hypotheses of the thesis:

1. Broad-scale bathymetric data of the U.S. Atlantic margin collected for ECS and deep sea exploration purposes are useful to consistently classify ecological marine units of the seafloor and generate value-added characterization maps of large regions.

2. Transparent, repeatable, and efficient semi-automated geomorphic analysis methods employing the Coastal and Marine Ecological Classification Standard (CMECS) as an organizational framework produce useful habitat characterization maps of the U.S. Atlantic margin.

Chapter 4 focused on the third hypothesis of the dissertation: that vulnerable cold-water coral (CWC) habitats are identifiable and able to be inventoried and characterized using geomorphic analysis and CMECS classification of bathymetric data. To test this hypothesis, the approaches refined in Chapters 2 and 3 were applied to a bathymetric grid compiled of all available high quality multibeam surveys on the Blake Plateau that had at least some topographic features indicative of CWC mounds. Study results identified 59,760 individual peak features, the vast majority of which are very likely to be CWC mounds based on their morphology and the validation provided by numerous submersible ground-truth dives completed on mound features in the region. The geomorphic classification efficiently delineated and inventoried five distinct landform classes from the bathymetry: peaks (342 km^2), valleys (2,883 km^2), ridges (2,952 km^2), slopes (15,227 km^2), and flats (49,003 km^2). Inner and outer search radii and the flatness parameter in BRESS were iteratively tested until an inner search radius of 1 grid node (35 m distance), an outer search radius of 6 grid nodes (210 m), and a flatness parameter of 1.5 degrees was found to yield the best results. The complex geomorphology of eight subregions was described qualitatively with geomorphic "fingerprints" and quantitatively by measurements of mound density and vertical relief, providing a thorough first-order characterization of the overall Blake Plateau CWC mound province.

All of the results from this chapter were conveyed directly to stakeholders via a presentation to the Habitat Protection and Ecosystem-Based Management Advisory Panel for the South Atlantic Fishery Management Council. Panel members expressed the usefulness of the interpreted mapping and characterization information in supporting their EBM approach to management and for informing their ongoing conservation measures to protect vulnerable CWC habitat.

Based on insights from research completed in Chapters 2-4, the following section summarizes the main contributions of this thesis to the field of marine habitat mapping and characterization.

Contribution to Advances in Marine Geomorphic Analysis and Classification Methods:

- The study area addressed in this thesis fills a gap in the field since few habitat mapping studies have been reported covering slope or abyssal habitats (Harris and Baker, 2011b).
- This thesis demonstrated the flexibility and effectiveness of the BRESS approach to terrain analysis for the delineation of landform features of interest. Benefits of the approach included the transparency and reproducibility of results, computational efficiency, concurrent production of spatial statistics layers derived from the bathymetry, time-saving proficiency compared to manual interpretation and delineation of features, and its scalability to large regions. The line-of-sight analytical approach provides benefits in its ability to self-scale to features in the terrain as versus fixed neighborhood moving window algorithms.
- The classification of geomorphic landforms using the study methods involved far less subjectivity than classification methods conducted manually via expert interpretation.

Manual delineation of these features over complex large regions in a consistent repeatable manner with a comparable level of detail would not be possible.

Contribution to Standardized Classification and Terminology

- This study was one of only several completed to date testing the application of CMECS to deep sea habitats (Bassett et al., 2017, Etnoyer et al., 2018, Ruby, 2017; Weaver et al., 2013).
- This research effort, along with key input from NOAA's Deep Sea Coral Research and Technology Program, prompted changes to NOAA OER's substrate annotation scheme used in real-time during ocean exploration dives on NOAA Ship *Okeanos Explorer* and for post-dive analysis of video data using Ocean Network Canada's SeaTube interface. This is a major advancement in the tangible implementation of CMECS terminology in the realm of deep sea exploration.
- This study identified specific gaps in CMECS units for deep sea areas and proposed new relevant provisional units for consideration (refer to Table 2.2, Table 3.1, and Table 4.2 for specific recommendations). CMECS is designed to be a dynamic content standard that evolves over time in response to field applications of the standard.

Contribution to Advancing Ecosystem-Based Management (EBM):

- The methods used in this thesis effectively translated bathymetry data into geomorphic landforms (and where possible into CMECS geoforms) useful for characterizing marine landscapes and inventorying the relative abundance or scarcity of general habitat types, which is informative to marine spatial planning efforts.

- As stated in the introduction to this thesis, technologies to map marine habitats are rapidly evolving and the demand for marine habitat maps is dramatically increasing. Maps serve as the fundamental basis for marine spatial planning. The methods developed and applied in this thesis are adaptable to data collected with different sensors and resolutions. The BRESS landform analysis tool can utilize bathymetry data independent of the technology used to generate the data. CMECS is also designed to be data agnostic. Both of these tools can be utilized for seafloor classification work that remains relevant as seafloor mapping technologies such as AUVs enable higher resolution data for deep sea habitats.
- As demonstrated in Chapter 4, the study methods have proven to be effective at identifying, quantifying, and characterizing CWC mound features. Protection of these vulnerable marine habitats requires this information in order to effectively implement EBM strategies.
- Because the methods are scalable to very large ocean regions, they will be useful for interpreting data collected at regional scales across political boundaries and in international waters. The U.S. has established a policy goal of mapping all the marine areas in its exclusive economic zone (EEZ) deeper than 200 m by 2030 (Ocean Science and Technology Subcommittee, 2020). The Seabed 2030 initiative is facilitating international cooperation towards the ambitious goal of mapping the global deep ocean by 2030 (Mayer et al., 2018). The extensive bathymetric datasets generated by this effort will be of exceptional intrinsic value by revealing the shape of the seafloor in far more detail than previously possible. However, the value of these data to support EBM will be leveraged far more significantly if they are further used to characterize marine habitats of the deep sea in a standardized manner of direct use by ocean scientists and managers to support decision-making.

- The objectively generated full-coverage spatial geomorphology layers produced by this thesis offer strong potential as a valuable input into coral habitat suitability models of the regions analyzed. Many species of deep sea corals show particular affinities for high-relief hard substrate features found on mound peaks and ridges. Utilizing fine scale delineations of these features as model inputs - or weighted spatial filters for fine tuning output probabilities - may result in more accurate models with improved predictive performance. Spatial layers generated by this thesis have been conveyed to coral modelers involved in the DEEP SEARCH initiative to test this hypothesis.
- Maps of geomorphic features created by this thesis may provide new insights into distribution patterns of deep sea fauna. Specific species or community assemblages may exhibit affinities for specific types of geoforms, revealing habitat preferences that may not be apparent when statistically analyzing biological data for correlations with standard environmental parameters (e.g. depth, temperature, pH, oxygen, etc.).

This dissertation has successfully characterized the geomorphology of vast regions of the deep ocean floor off the U.S. Atlantic margin for ecosystem-based management purposes. It has applied techniques and established standards of classification that can be applied to other regions throughout the World. This latter point is critical as there are ongoing international efforts today to map the entirety of the World's oceans at meaningful scales and these techniques can synthesize this information in meaningful ways. Furthermore, the need for such syntheses is paramount in order to successful manage (conserve and preserve) the living and non-living resources of the ocean. This thesis shows a way forward for such endeavors, and emphasizes 1) the applicability of data acquired for other purposes to be applied to this purpose, and 2) the need for standards to define and describe marine habitats so that all governments, managers, biologists, geoscientists, and other ocean stakeholders communicate using the same language.

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